

# Sound transmission in cross-laminated timber buildings

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Master Thesis







# SOUND TRANSMISSION IN CROSS-LAMINATED TIMBER BUILDINGS

A numerical approximation of the sound transmission through CLT  
elements and junctions

by

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in accordance with the requirements for obtaining the degree of

**Master of Science**  
in Civil Engineering

at the Delft University of Technology,  
to be defended publicly on Tuesday, March 22, 2022 at 09:00

Student number: 4456424

Project duration: June, 2021 – March, 2022

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# PREFACE

With this thesis I will finalize my master's study in Building Engineering with a specialization in Structural Design. The thesis is about the prediction of the flanking sound transmission in cross-laminated timber (CLT) junctions in apartment buildings. I hope that this research will be beneficial for the CLT building industry and I am curious about the future developments in this research field.

The research was carried out for the University of Technology Delft, in collaboration with ZRI, a company specialized in building physics, and Goudstikker de Vries, a constructively oriented engineering firm. I want to express my gratitude towards the members of ZRI and Goudstikker, for making me feel welcome at their offices, especially during these Covid times. A special thanks to my company supervisors Anika Haak and Mandy van Lunteren - van Zaanen for their supervision and guidance over the last couple of months. I would also like to thank my graduate committee for their guidance, comments, and knowledge. A special thanks to Maria Felicita for our weekly meetings, helping me with struggles, and keeping me motivated.

Besides, I want to thank my study friends for all the hard needed coffee and lunch breaks together. Every temptation coffee was very well deserved. Last but not least I want to thank Henriët, Berber, and Joost for all their love and support during my studies. Dad, I am an engineer now!

*I.E. Bos  
Delft, University of Technology, March 2022*





# ABSTRACT

Low-frequency sound transmission in a cross-laminated timber apartment building can result in annoyance, even if the acoustic requirements of the building code are fulfilled. Cross-laminated timber is an upcoming material in the building industry. The material is popular as it could be a solution to build the required homes without exceeding the nitrogen and carbon dioxide emission norms. But there are also problems arising when building with this relatively new material. CLT is a lightweight building material, which means that the mass itself is insufficient for meeting the acoustical requirements. The total sound transmission depends on the amount of direct sound and flanking sound transmission. The ISO 12354 standard used to determine the amount of sound transmission between rooms does not include frequencies below 100 Hz. Even though these low-frequency sounds are the main cause of annoyance in lightweight construction buildings. The low-frequency sound transmission is hard to measure because of the long wavelength. In this research, a numerical model was developed and used to determine the low-frequency sound transmission in CLT apartment buildings.

The effect of the following sound-reducing measures are studied: the material properties of the material CLT, additional linings on the room separating elements, use of elastic interlayers between CLT panels and the type and number of connectors connecting the CLT panels. These are all common sound-reducing measures for lightweight constructions. The effect of the material properties of the CLT and the effect of additional linings are computed by a numerical direct sound transmission model. The effects of elastic interlayer and connectors between the CLT panels are computed with a numerical vibration reduction index model. The results of the numerical models are compared to measurements found in literature and the sound transmission according to the ISO standard. A difference of 3 dB is not noticeable by humans, 5 dB can make the difference between an acceptable level and annoyance and 10 dB is a doubling of the loudness.

The results showed the importance of Young's modulus in the y and z-direction, these influence the location of the resonance induced dips in the sound insulation. The internal loss factor of the CLT panels influenced the height of the dips. A loss factor of 20 % resulted in results most similar to the measurements. The direct sound transmission through a bare CLT panel can be predicted within a range of 3 dB difference with measurements. The prediction of the ISO standard is within a range of 5 dB with the measured values.

The vibration reduction index between panels without interlayers is modelled with frictional contact regions between the panels. The numerical results showed similarities with the measurement results for the vibration reduction index of panels with screwed connectors. The ISO standard significantly overpredicts the vibration reduction index of CLT junctions. The effect of the elastic interlayer showed insignificant improvements in the frequency range 50-500 Hz, the additional reduction stays below 3 dB. The ISO standard does not include a method to determine the effect of elastic interlayers or connectors between CLT panels.

The numerical models prove that is possible to predict the low-frequency sound transmission in CLT apartments. Important notes are that the CLT lamellas need to be modelled separately. Only in this way the model is able to capture the sound that goes through a structure within a range of 3 dB. In order to test the effect of additional lining, the material properties need to be known. The vibration transmission between panels in the junctions is more complex, as it depends on more design parameters. A frictionally bonded contact region between the panels results in vibration reduction indices that are in line with measurement results of panels with several connectors. The effect of the elastic interlayer is minimal in the low-frequency range, but the results are similar to measurement results. Both the direct sound transmission model and the vibration reduction model were influenced by the boundary conditions.

The numerical model becomes computationally expensive. Therefore the effect of the connectors was not investigated due to the size of the models. In order to be able to predict a large number of build-ups, it would be beneficial to be able to reduce the model size. The influence on the accuracy of the results should be investigated. When using the building code for predicting the sound transmission in a CLT building it should be kept in mind that the results are not conservative. The sound transmission on-site could be significantly higher than predicted.





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# NOMENCLATURE

$[C]$	Damping matrix [-]
$[K]$	Stiffness matrix [-]
$[M]$	Mass matrix [-]
$[R]$	Coupling matrix [-]
$\alpha$	Angle [-]
$\Delta L$	Impact sound improvements due to additional layers [dB]
$\Delta R_i$	Sound reduction index improvements due to additional layers of element i [dB]
$\Delta R_j$	Sound reduction index improvements due to additional layers of element j [dB]
$\Delta R_{Dd,w}$	Improvement of the total weighted sound reduction index by additional lining [dB]
$\Delta R_{ij,w}$	Improvement of the total weighted sound reduction index by additional lining on the flanking element ij [dB]
$\eta$	Internal loss factor [-]
$\gamma_M$	Partial factor for material properties [-]
$\gamma_{0,i}$	Safety factor [-]
$\lambda$	Wavelength [m]
$\omega$	Analysed frequency [Hz]
$\rho$	Density [kg/m <sup>3</sup> ]
$\rho_k$	Characteristic minimum value of bulk density [kg /m <sup>2</sup> ]
$\rho_{mean}$	Mean bulk density [kg /m <sup>2</sup> ]
$\tau'$	Total sound transmission factor [-]
$\tau_d$	Direct sound transmission factor [-]
$\tau_f$	Flanking sound transmission factor [-]
$\tau_s$	Indirect sound transmission factor [-]
$\zeta$	Constants damping parameter [-]
$A$	Average sound absorption coefficient receiver room [-]
$A_0$	Reference equivalent absorption area (for dwellings $A_0 = 10 \text{ m}^2$ ) [m <sup>2</sup> ]
$a_{i,situ}$	In-situ equivalent absorption length of the element i [m]
$a_{j,situ}$	In-situ equivalent absorption length of the element j [m]
$c$	Speed of sound [m/s]
$d$	Diameter of the fastener [mm]
$D_{nT;A;k}$	Characteristic A weighted normalized airborne sound reduction [dB(A)]

$D_{nT;A}$	A weighted normalized airborne sound reduction [dB(A)]
$D_{v,ij,situ}$	Junction velocity level difference between elements i and j, [dB]
$E_x$	Young's modulus in the x-direction [MPa]
$E_y$	Young's modulus in the y-direction [MPa]
$E_z$	Young's modulus in the z-direction [MPa]
$E_{m,0,k}$	5 percentile modulus of elasticity parallel bending [ $\text{kg / m}^2$ ]
$E_{m,0,mean}$	Mean modulus of elasticity parallel bending [ $\text{kg / m}^2$ ]
$E_{m,90,mean}$	Mean modulus of elasticity perpendicular [ $\text{kg / m}^2$ ]
$f$	Frequency [Hz]
$f_0$	Mass-spring resonance frequency [Hz]
$F_{ax,\alpha,rk}$	Withdrawal resistance [N]
$F_{ax,rd}$	Design value of axial withdrawal capacity of the fastener [ $\text{N/mm}^2$ ]
$F_{ax,rk}$	Characteristic axial withdrawal capacity of the fastener [ $\text{N/mm}^2$ ]
$f_{c,0,k}$	Characteristic compressive strength parallel to the grain [ $\text{N/mm}^2$ ]
$f_{c,90,k}$	Characteristic compressive strength perpendicular to the grain [ $\text{N/mm}^2$ ]
$f_{h,k,perp}$	Characteristic embedment strength perpendicular [ $\text{N/mm}^2$ ]
$f_{m,k}$	Characteristic mean bending strength [ $\text{N/mm}^2$ ]
$F_{max}$	Maximal load [kN]
$f_{ref}$	Reference frequency [Hz]
$f_{t,0,k}$	Characteristic tension strength parallel [ $\text{N/mm}^2$ ]
$f_{t,90,k}$	Characteristic tension strength perpendicular [ $\text{N/mm}^2$ ]
$f_{v,k}$	Characteristic shear strength [ $\text{N/mm}^2$ ]
$F_{v,rd}$	Design load-carrying capacity per shear plane per fastener [ $\text{N/mm}^2$ ]
$F_{v,rk}$	Characteristic load-carrying capacity per shear plane per fastener [ $\text{N/mm}^2$ ]
$G_{k,i}$	Characteristic value of a permanent action i [ $\text{kN/m}^2$ ]
$G_{mean}$	Mean shear modulus [ $\text{kg / m}^2$ ]
$G_{xy}$	Shear modulus in the x-z plane [MPa]
$G_{xz}$	Shear modulus in the x-y plane [MPa]
$G_{yz}$	Shear modulus in the y-z plane [MPa]
$K$	Bulk modulus [ $\text{N/m}^2$ ]
$K_{ij}$	Vibration reduction index for path ij [dB]
$k_{mean}$	Mean stiffness of the connection [kN/mm]
$k_{mod}$	Modification factor [-]
$K_{ser}$	Slip modulus [kN/mm]

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$l$	Length [mm]
$L'_{nT}$	Standardized impact sound pressure level [dB]
$l_0$	Reference coupling length of 1 [m]
$L_i$	Impact sound pressure level measured in the receiving room [dB]
$l_{eff}$	Penetration depth of the screw [mm]
$l_{ij}$	Length of junction between elements i and j [m]
$L_{n,d}$	Normalized impact sound pressure level due to direct transmission [dB]
$L_{n,ij}$	Normalized impact sound pressure level due to flanking transmission [dB]
$L_{nT,w}$	Weighted standardized impact sound pressure level between the two rooms [dB]
$L_{nT,A;k}$	Characteristic A weighted normalized impact sound pressure level [dB(A)]
$L_{nT,A}$	A weighted normalized impact sound pressure level [dB(A)]
$L_{nT,i}$	Standardized impact sound pressure level for element i [dB]
$L'_n$	Total impact sound pressure level in the receiving room [dB]
$n$	Number of fasteners [-]
$n_{eff}$	Number of effective fasteners [-]
$P$	Acoustic pressure [W]
$Q_{k,i}$	Characteristic value of the variable action i [kN/m <sup>2</sup> ]
$R_i$	Sound reduction index of component i [dB]
$R_j$	Sound reduction index of component j [dB]
$R_w$	Weighted sound reduction index [dB]
$R_{Dd,w}$	Weighted sound reduction index of the separating element [dB]
$R_{i,w}$	Weighted sound reduction index of flanking element i [dB]
$R_{ij}$	Flanking sound reduction index [dB]
$S$	Area of separating element [m <sup>2</sup> ]
$S_i$	Area of element i [m <sup>2</sup> ]
$S_j$	Area of element j [m <sup>2</sup> ]
$S_s$	Area of separating element [m <sup>2</sup> ]
$S_s$	Area of separating elements [m <sup>2</sup> ]
$T$	Reverberation time in the receiving room, [s]
$t$	Thickness [mm]
$T_0$	Reference reverberation time (for dwellings : $T_0 = 0,5$ s) [s]
$T_s$	Structural reverberation time [s]
$V$	Volume of the receiver room [m <sup>3</sup> ]
$v$	Mean surface vibration velocity [m/s]

---

$\nu_{xy}$	Poisson's ratio in the x-y plane [-]
$\nu_{xz}$	Poisson's ratio in the x-z plane [-]
$\nu_{yz}$	Poisson's ratio in the y-z plane [-]
$w$	Width [mm]
$Z$	Specific acoustic impedance [Ns/m <sup>3</sup> ]
$p$	Acoustic fluid pressure vector [-]
$u$	Displacement vector [-]

## ACRONYMS

CLT	Cross-Laminated Timber
FE	Finite Element
FEA	Finite Element Analysis
FEM	Finite Element Model
FSI	Fluid Solid Interface
SEA	Statistical Energy Analysis
SLS	Serviceability Limit State
SPL	Sound Pressure level
ULS	Ultimate Limit State



# 1

## INTRODUCTION

### 1.1. RESEARCH CONTEXT

The building industry is the number one industry when it comes to the use of non-renewable resources. The industry has a lot of experience with working with traditional building materials like concrete and steel. Therefore, the industry obtained a lot of knowledge about how to work with these materials and thus the involved risks are lower than working with new materials like cross-laminated timber. In this way, companies can reduce their prices and attract more clients. By going through this cycle of gaining knowledge, reducing risks and lowering their costs over and over again the building industry created a lock-in problem. Jones, Stegemann, Sykes and Winslow (2016) [39] suggested that 'locked-in companies lack the commercial opportunity and hence motivation, rather than the capability, to adopt approaches perceived to increase cost or risk.' Companies will therefore tend to resist unconventional approaches, restricting the physical opportunity for other project participants. This makes it harder for new building materials like cross-laminated timber to enter the market. There is less knowledge available about the material CLT which results in higher risks.

The world is becoming more aware of the environmental impact of the building industry. So, over the last couple of years, the building industry in the Netherlands has become more interested in building with timber materials like CLT [40]. Building residential housing with timber is nothing new, as wood products were already used as a building material in the stone age. But over the last couple of years new engineered wood products have been developed, these products are gaining popularity in the modern world. Cross-laminated timber is one of these products. Timber lamellas are glued together in a cross-wise manner, creating the CLT panel. Building with mass timber could be a solution to build the required homes without exceeding the nitrogen and carbon dioxide emission norms. As one of the advantages of timber is that the material itself can lock up carbon, in this way building with CLT could result in very sustainable buildings [41]. Another advantage is that most building elements can be produced prefab which results in a clean and dry construction site. Also, the construction time of CLT buildings is very short compared to the construction time of concrete buildings. But there are also problems arising when building with this relatively new material. For example, there are concerns about the fire safety of timber structures and since CLT is a lightweight material more attention is needed to meet the acoustic requirements [2].

The connection between the CLT wall and floor panels influences the amount of sound transmitted from one element to the other. The mass of the elements has a large influence on the amount of sound transmission. The density of CLT is much lower than the density of concrete or other stony materials. Therefore the mass of the CLT panel alone is not enough to reduce the flanking sound transmission to acceptable levels. Most studies into the sound reduction between apartments focus on the direct sound transmittance between the rooms. The better the direct sound reduction the higher the influence of the flanking sound transmission becomes. Full decoupling of the CLT wall and floor elements would reduce most of the sound transmission but this would result in unstable connections. Here lies the conflict between the acoustic advisor and the structural engineer. By gaining a better understanding of the sound transmission through CLT junctions and the impact of different sound-reducing measures, the performance of future junctions can be predicted better. In this way, the acoustical performance of CLT buildings can be improved.

## 1.2. PROBLEM DEFINITIONS

When a building is designed there are several acoustic challenges to overcome: airborne sound transmission, impact sound transmission, flanking sound transmission, outdoor noise transmission and installation noise transmission [17]. For traditional building materials, the mass is usually able to reduce the sound transmittance to acceptable levels. The mass law states that by doubling the mass of the separating element the sound insulation will increase by 5 á 6 dB [42]. For lightweight materials like CLT, the mass of the separating element itself is insufficient for the required sound reduction. A CLT element should be over 1 meter thick to meet the required sound reduction for the direct sound transmission. So especially for building types with high acoustic requirements, such as residential buildings, the connection details need to be designed properly. Only in this way it is possible to reach the sound reduction levels which are stated in the Dutch 'Bouwbesluit 2012'. In this research, the aim is to fulfil the Dutch requirements. In other countries, the requirements can be slightly different.

The 'Bouwbesluit 2012' only gives requirements for the sound insulation in the frequency range of 1/3 octave bands from 100 Hz to 3150 Hz. Literature states that the transmission of low-frequency sound can cause annoyance for the residents. This is a problem especially for lightweight building materials, as lightweight materials are more sensitive to vibrations [43]. With low frequencies, the 1/3 octave bands 50, 63 and 80 Hz are meant.

In lightweight buildings, it is common to use additional linings like retention walls, floating screeds and drop ceilings. In this way, the direct sound transmission is reduced. But the flanking sound transmission remains a point of concern. In lightweight constructions up to 80% of the sound transmittance between apartments can be attributed to flanking sound transmission [44]. Therefore only taking measures to reduce the direct sound transmission will not directly result in meeting the requirements for the maximally allowed sound transmission between apartments. The flanking sound reduction value does not only depend on the sound insulation value of the single building components but mainly on the connection between these building components. Often parts of the main load-bearing structure come together in these junctions. In this way, the load-bearing structure plays an important role in the flanking sound transmission [45]. Fully disconnecting the apartments would be optimal for the sound reduction but this would cause stability issues. This is where the conflict arises between the acoustical and structural requirements. The structural engineer and the acoustics advisor have to work together to come to an optimal solution and create a junction with the required load-bearing capacity and at the same time reduce the flanking sound transmittance.

A lot of research focuses on how to reduce the direct sound transmittance in buildings made out of CLT. Only a few studies focus on the flanking sound transmittance in CLT junctions. In most cases, only the performance of a specific system of a CLT manufacturer is measured. This makes it hard for acoustical advisors to predict the total sound reduction level between apartments when the configuration differs from measured cases. Therefore for large projects, experimental tests are needed, which are expensive and time-consuming. For smaller projects, experiments are not achievable, which could lead to a significant underestimation of the sound transmission. If this is the case, adjustments must be carried out to the building on site.

## 1.3. AIM AND OBJECTIVES

The goal of this project is to be able to determine the total sound transmission between two rooms in an apartment building with a cross-laminated timber structure. The total sound transmission includes both the direct sound transmission and the flanking sound transmission. Based on the predicted sound transmission acoustical engineers can give more accurate and better-substantiated advice during the design phase. To reach the goal of this research the following objectives must be reached first:

- Determine the effect of different sound-reducing measures
- Develop a numerical model which determines the sound transmission through a CLT construction and the effect of different material properties and sound-reducing measures
- Determine the amount of total sound transmission (flanking and direct) between two apartments in a CLT construction

## 1.4. RESEARCH QUESTIONS

The report consists of 8 chapters, all answering one or more sub-questions. Answering the individual sub-questions will lead to an answer to the main research question:

*'How can the effect of sound-reducing measures on the direct and flanking sound transmission between two rooms in a cross-laminated timber apartment building be modelled in order to predict the total sound transmission?'*

### CHAPTER 2 – LITERATURE REVIEW

The literature review touches upon three different topics. First, building with the material cross-laminated timber to determine the constraints for building with cross-laminated timber. Second, the basic principles of sound among other things determine how to quantify the total amount of direct and flanking sound transmission. Third, the building codes concerning sound transmission. The knowledge gained in this chapter creates the base for the numerical sound transmission models.

### CHAPTER 3 - SOUND REDUCING MEASURES

The goal of this chapter is to give insight into the different types of sound-reducing measures and the effect on the amount of sound transmission between rooms. The measurement data collected from the literature will be used to verify the sound transmission models.

- What measures affect the total amount of sound transmission between rooms in cross-laminated timber buildings?
- What is the measured effect of different sound-reducing measures?

### CHAPTER 4 - NUMERICAL SOUND TRANSMISSION MODEL

This chapter focuses on the development of a sound transmission model. The model needs to be capable of calculating the effect of different sound-reducing measures.

- How can a sound transmission model be developed?

### CHAPTER 5 - SENSITIVITY ANALYSIS

The sensitivity of the sound transmission models to different materials and design parameters will be tested. The most influential parameters will be identified.

- Which material and design parameters have the most influence on the sound transmission?

### CHAPTER 6 - RESULTS AND OBSERVATIONS

The results of the sound transmission model will be given and compared to measured data and the results of the ISO standard. The goal is to verify the results of the numerical models.

- What is the difference between the amount of sound transmission calculated by a sound transmission model, measured results and the calculated sound transmission according to the ISO standards?

### CHAPTER 7 - DISCUSSION

In this chapter the results and observations will be discussed. Design assumptions and decisions will be reviewed and the influence on the results discussed.

### CHAPTER 8 - CONCLUSION AND FUTURE RESEARCH

This chapter finalizes the research. The main research question will be answered based upon the answers to the sub-questions. Lastly, the limitation of the project will be discussed to conclude with points for future research.

### 1.5. SCOPE

The scope of this research is limited to the structural and acoustic requirements. Fire safety is an important aspect in the design of CLT junctions but will not be considered explicitly in this research. But, 3-ply elements will not be considered in this research due to fire safety issues.

The estimation of the sound transmission through the structure will be studied with finite element models. Using FEM is computationally expensive and this often limits the frequency range (to the low and mid-frequencies) and/or the dimensions of the structures that can be studied and/or the number of details that can be included in the geometry. This is mainly a problem when dealing with vibroacoustic problems with a large frequency spectrum of interest or sensitivity analyses where a high number of different situations need to be investigated.

# 2

## LITERATURE STUDY

This chapter presents the literature review that defines governing aspects and strategies relating to the building constraints for building with cross-laminated timber and the quantification of the amount of sound transmission. Section 2.1 covers the timber constraints: material properties, building methods and connection methods. Section 2.2 covers the basic principles of sound and determines the frequency range of interest. Section 2.3 summarizes the sound insulation rules, regulations in the Netherlands and the ISO standard for determining sound transmission.

### 2.1. CROSS LAMINATED TIMBER

Wood is an organic and natural material and therefore has a more complex mechanical behaviour. The mechanical properties of wood depend on the growth of a tree. A tree can grow in height and thickness. This makes wood an orthogonal an-isotropic material, which means that the material has three different material properties in the three main directions. This is also called an orthotropic material. The longitudinal (L) direction is oriented parallel to the fibres, the tangential (T) direction is tangential to the fibres and the radial (R) direction is radial to the fibre direction. These three directions can be linked to the x, y and z directions of the Cartesian coordinate system, as shown in figure 2.1.

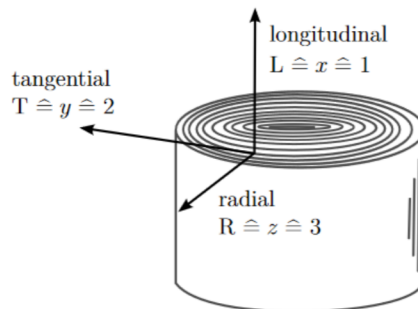


Figure 2.1: Principle directions in wood [1]

#### 2.1.1. MATERIAL PROPERTIES

The tangential and radial directions used for wooden planks are both called perpendicular( $\perp$ ) for CLT lamellas. This is because of the way the lamellas are cut in the factory. Manufacturers do not make a distinction between lamellas that are cut in the tangential or radial direction. Parallel( $\parallel$ ) to the fibres is still called the longitudinal direction. Therefore the properties of engineered timber elements can be described by six constants instead of the nine constants needed for wood [1].

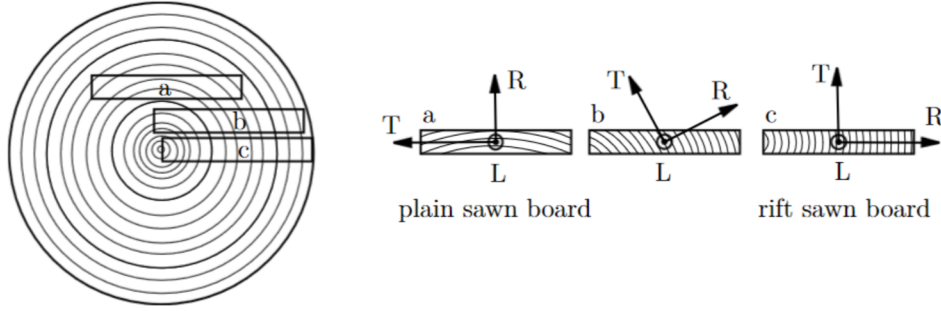


Figure 2.2: Lamellas sawn from a tree trunk [1]

- $E_{\parallel} = E_x$
- $E_{\perp} = E_y = E_z$
- $G_{\parallel\perp} = G_{xy} = G_{xz}$
- $G_{\perp\perp} = G_{yz}$
- $\nu_{\parallel\perp} = \nu_{xy} = \nu_{xz}$
- $\nu_{\perp\perp} = \nu_{yz}$

The material properties of a CLT element are highly dependent on the species used. Also, the moisture content and loading direction are of influence. For the production of CLT, the most used wood type is spruce with a strength class of C24 [38]. The interaction between the layers has a significant impact on the strength and an-isotropic behaviour of the material. For layers with a thickness above 10 mm the density of the adhesive in between the layers is not significant for the total density of the material [38]. CLT panels are glued together between the faces of the elements in adjacent layers. It is also possible to use glue to bond the adjacent elements within a layer, as the gaps between the lamellas within a layer can be up to a few mm.

Density	Symbol	C24	Unit
Characteristic minimum value of bulk density	$\rho_k$	350	$kg/m^3$
Mean bulk density	$\rho_{mean}$	420	$kg/m^3$

Table 2.1: Density of the C24 lamellas [29]

Stiffness	Symbol	C24	Unit
Mean modulus of elasticity parallel bending	$E_{m,0,mean}$	11,0	$kN/mm^2$
5 percentile modulus of elasticity parallel bending	$E_{m,0,k}$	7,4	$kN/mm^2$
Mean modulus of elasticity perpendicular	$E_{m,90,mean}$	0,37	$kN/mm^2$
Mean shear modulus	$G_{mean}$	0,69	$kN/mm^2$

Table 2.2: Stiffness properties of the C24 lamellas [29]



Strength	Symbol	C24	Unit
Bending	$f_{m,k}$	24	$N/mm^2$
Tension parallel	$f_{t,0,k}$	14,5	$N/mm^2$
Tension perpendicular	$f_{t,90,k}$	0,4	$N/mm^2$
Compression parallel	$f_{c,0,k}$	21	$N/mm^2$
Compression perpendicular	$f_{c,90,k}$	2,5	$N/mm^2$
Shear	$f_{v,k}$	4,0	$N/mm^2$

Table 2.3: Strength properties of the C24 lamellas [29]

Cross-laminated timber is a type of engineered wood and is assembled out of at least three layers of solid timber lamellas. These lamellas are glued together under high pressure. The grain direction of adjacent lamellas is perpendicular to one another. The layout of the lamellas has to be symmetrical, so there is always an uneven number of panels. The elements can bear loads in and out of plane [7]. A higher number of layers will also result in an element that acts more as an isotropic material since the bending stiffness of the primary axes become more equal. So a 3-ply plate is more like an an-isotropic element than a 7-ply plate. The common and available sizes of CLT panels are given in table 2.4. In figure 2.3 a CLT panel is shown. The edges of the panel are also called the narrow faces. The large face of the panel is called the side face.

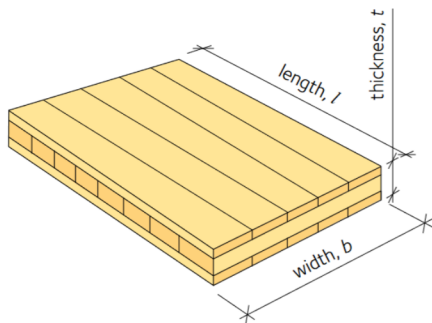


Figure 2.3: Build-up of a CLT panel [2]

Parameter	Common	Available
Thickness, t	80-300 mm	60-500 mm
Width, w	1.2-2.0 m	Up to 4.8 m
Length, l	16 m	Up to 30 m
# of layers	3,5,7,9	Up to 25

Table 2.4: Common and available sizes for CLT panels [2]

Eurocode 5 contains the general rules for timber construction [46]. The material cross-laminated timber is not included in the Eurocode 5. The Eurocode is being revised at this moment in time. The aim is to include the material CLT in the upcoming updated version of the code. Each CLT producer provides information in a national or European technical approval (ETA). These documents include details about the product.

### 2.1.2. STABILITY SYSTEMS

For this research, the constraint is that cross-laminated elements will be used for both the walls and floors of the structure. There are several ways to provide stability in this case. The stability system influences the type of connections needed in the junctions. Here a few options are explained. One of these stability systems will be chosen to narrow down the scope of the research.



Figure 2.4: Examples of stability systems A) Shear wall [3] B) Core system [4] C) Tube system [5] D) Diagrid system [6]

### RIGID FRAME

For this type of stability system, the load-bearing elements are rigidly connected to the horizontal elements. The horizontal and vertical loads can transfer bending moments. Rigid joints are difficult to create for timber structures. Therefore this type of stabilization is not suitable for CLT buildings.

### SHEAR WALL SYSTEM

A shear wall system consists of vertical walls which transfer the lateral and gravitational loads. With this system, the connection between the elements is crucial for the load-bearing capacity and stiffness of the structure. The floors act as diaphragms that transfer their loads to the shear walls. The connection between the floor and wall elements need to be able to transfer the lateral forces. Examples of buildings with CLT shear walls are hotel Jakarta in Amsterdam, Stadthaus London and the Forte Tower in Melbourne. The maximal building height for buildings with CLT shear walls is limited.

### CORE SYSTEM

A core system is similar to the shear wall system. The difference is that the shear walls are placed together to create a core. With a core stability system, one or more cores provide the stability of the structure. All the horizontal forces are transferred to the core. The core can be made out of concrete or CLT. The other walls in the building can be made out of CLT. The connections between the floors and these non-shear walls only need to be able to resist the vertical loads. Examples of buildings with a concrete core are the BrockCommons Tallwood building in Vancouver, HAUT in Amsterdam, SAWA in Rotterdam (in concept) and HoHo in Vienna. The use of a CLT core has been researched but at this moment in time, there is no building with a CLT core realized.

### TUBE SYSTEM

In a tube system, the facade is load-bearing and bears the lateral loads. The facade element can for example be made out of CLT panels or glulam braces. The number of openings should be limited to create a stiff tube that provides the building's stability. The walls and floors only carry the vertical loads. Examples of conceptual buildings with a CLT tube system are the Trätoppen in Stockholm (in concept) and the Treet in Bergen.

### DIAGRID SYSTEM

This system consists of elements that form a diagrid structure. The diagonals of the diagrid act as lattice girders. The diagonals are often positioned in the facade. As the diagonals take the lateral forces, no additional columns or cores are necessary for the stability of the building. Examples of conceptual buildings with a diagrid system are the River Beech Tower in Chicago and the Oakwood tower in London.

The shear wall system and the core system are the most popular stability systems for CLT buildings at the moment [7]. Other types of systems such as the tube system and the diagrid are being investigated to create higher timber buildings. But these types of stability systems are not commonly used at this moment in time. When comparing the load transfer through the junctions for a shear wall system and a core system



the junctions for a shear wall system are more complex. The additional complexity is because the junctions in shear walls systems cope with both the vertical and lateral loads. To bear the lateral loads the junctions need a certain stiffness that is not required for the junctions in a core system. To narrow down the scope of the research it is assumed that the stability of the building will be provided by a core. In this way, the junction between the apartments only needs to be verified for the vertical strength.

### 2.1.3. STRUCTURAL SYSTEM

The two most commonly used construction systems for CLT are platform construction and balloon construction [7]. In a platform construction, the floor panels rest on top of the walls. In this way, a platform is created for the next floor. The construction time can be very quick as the connections can be simple and the load path is clear. With this type of construction, it is important to make sure that the floor element can bear the compression forces, as the compression strength of timber perpendicular to the grain is relatively low. The maximal height for this type is limited to the compression resistance perpendicular to the grain on the lowest level. This type of construction is commonly used for buildings up to three to five stories [10].

For higher or heavily loaded constructions the most common way is the balloon type of construction [10]. In the balloon construction, the walls continue for a few floors. The floors are attached to the wall panel. The connection details are more complex for this system [7]. Both construction systems are shown in figure 2.5.

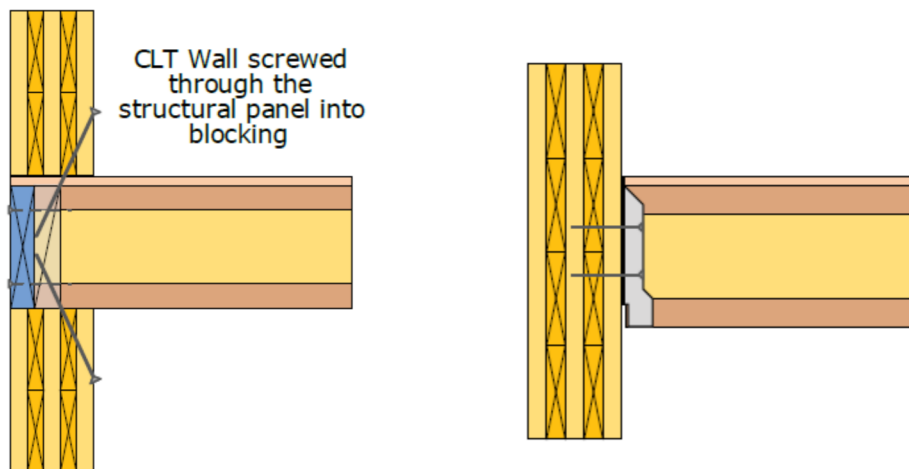


Figure 2.5: Platform and balloon construction [7]

### 2.1.4. CONNECTION TYPES

The connectors used in CLT junctions are important for the structural and acoustical requirements. The junctions must be able to transfer the loads and at the same time, the sound transmission must be limited. The material CLT is not a part of the Eurocode 5. Research showed that the behaviour related to the moisture content for CLT is similar to that of glulam [47].

Some common connector types for CLT constructions will be briefly explained. Only the wall-wall and wall-floor will be investigated, as these connections are of most importance for the flanking sound transmission. There are also connectors between the walls and the foundation and the in-line connections for floors but these will not be further explained as these connections are of less interest for the sound transmission. The connections types that will be touched upon are screws, angle brackets, hold-downs and the innovative X-RAD connection system.

#### SELF-TAPPING SCREWS

Self-tapping screws are the most used connectors in CLT buildings [8]. This type of fastener is easy to apply and therefore popular. The screws can take up axial and lateral loads. This type of connection can be used for wall-to-wall connections in-plane and perpendicular to each other or for connecting a wall to a floor. The length of the screws can be up to 1000 mm and the diameter can be up to 15 mm [7]. In some connections, the screws are not visible in the final structure in other locations the head of the screw will remain visible.

Eurocode 5 [7] gives equations to calculate the strength and stiffness of a connection made with screws. To calculate the shear strength of the connections different failure modes are considered. The failure mode with the lowest load capacity is governing. There are different failure modes for single shear planes or double shear planes. The different failure modes for timber to timber connections are shown in figure B.1 in the appendix. These failure modes describe either the failure of the CLT element or the failure of the connector. The Johnson equations can be found in appendix B.

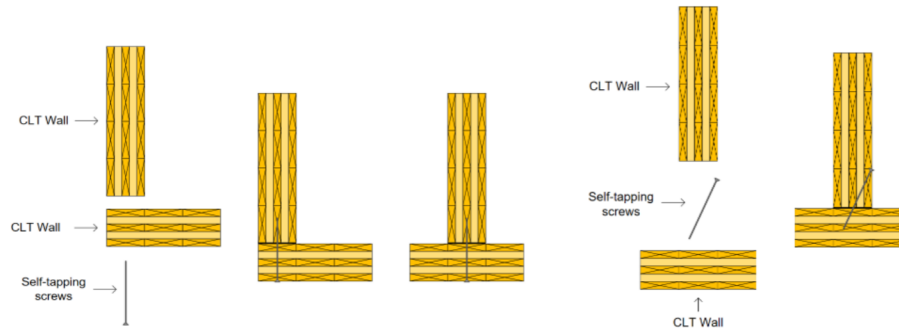


Figure 2.6: Screws perpendicular to the panel and under an angle [7]

It is also possible to drive the screws perpendicular into the panel or under an angle which is called toe-screwing. Toe-screwing has the preference as driving into the end grain is avoided, which will optimize the performance of the connection [7].

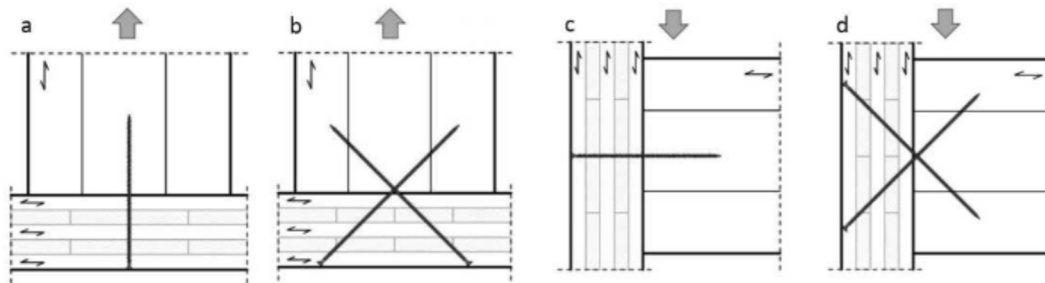


Figure 2.7: Screwed connections under axial and lateral load [8]

The Eurocode 5 does not include the material CLT. Therefore often additional tests are done to verify the strength and stiffness of the connection between CLT elements. Rothoblaas and Graz University both tested different types of connectors. In table 2.5 the measured values are given for the strength and stiffness of self-tapping screws.

Loading	Angle	$F_{max}$ [kN]	$K_{ser}$ [kN/mm]
(a) Axial	90	20,8	17,6
(b) Axial	45	33,6	16,6
(c) Lateral	90	10,3	0,5
(d) Lateral	45	30,0	19,9

Table 2.5: Measurements of the strength and stiffness of self tapping screws [8]

### ANGLE BRACKETS

Angle brackets are used to connect walls perpendicular to each other or walls to floors. The angle brackets are present for the transfer of shear forces but are also capable of transferring tensile forces. When connecting the wall and floor this type of connection can transfer the lateral loads. The transfer of these lateral loads is needed for a system with diaphragm floors and shear walls. This connection type is very efficient and simple to apply [7].

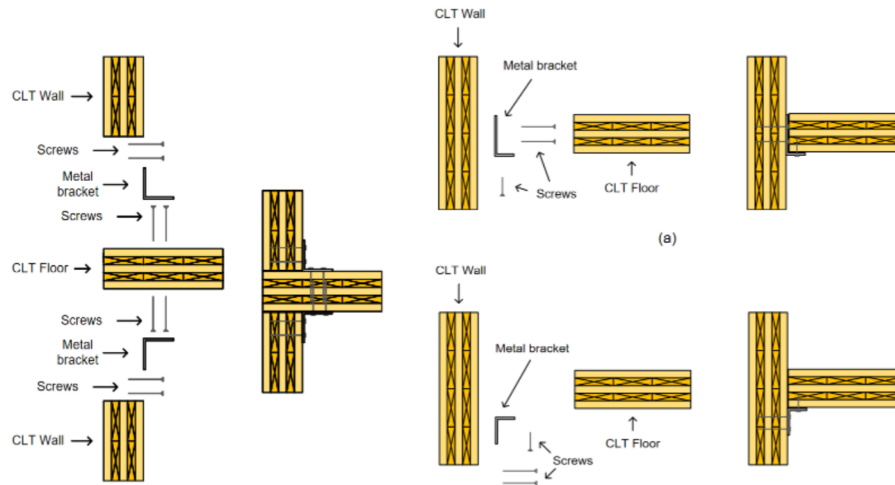


Figure 2.8: Use of angle brackets for a platform and balloon type of construction [7]

The strength of an angle bracket can be calculated with the Johanson formulas. Here the formulas for a timber-steel connection are valid. The formulas can be found in Appendix B. Angle brackets can be used in combination with nails or screws.

When an elastic layer is placed in-between two CLT elements the connectors will be subjected to larger bending moments. Due to this additional bending moment, the horizontal stiffness of the screws and therefore the load-bearing capacity will be reduced. The ISO code does not include additional formulas for when an elastic interlayer is applied. The ETA from Rothoblaas gives a few values for the load-bearing capacity of some connections with interlayers.

### X-RAD SYSTEM

The X-RAD system is a new connection system developed by Rothoblaas. At every corner of the CLT element, a standard connector is placed. The connector is connected to the CLT element with screws that are inserted under different angles. This connector type has several advantages: very precise and safe installation, quick execution and a reduced number of connections [9]. In addition, Rothoblaas designed the X-SEAL, a structure that covers the X-RAD connector and optimizes the acoustical comfort [9]. The seal does provide additional acoustic comfort but will be insight if the element has no additional lining.

As Rothoblaas developed this new type of connector they also tested the connection to verify the strength and stiffness of the connector. Results of these measurements can be found in table 2.6.

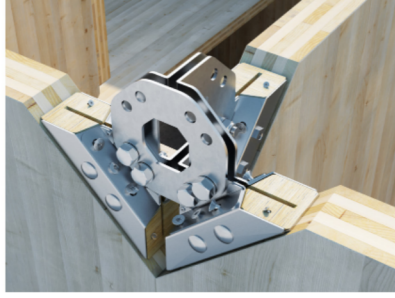


Figure 2.9: X-RAD connection system [9]

Angle	$F_{mean}$ [kN]	$k_{mean}$ [kN/mm]
45	171,2	23,6
135	108,9	9,0
0	128,9	11,8
180	185,8	13,4
225	289,6	23,0

Table 2.6: Measurements of the strength and stiffness of the X-RAD connector [9]

To cope with fire safety it should be mentioned that the connectors should always be protected. A common solution is to place gypsum boards in front of the CLT element with visible connectors [7].

### 2.1.5. CONNECTION VERIFICATION

#### WITHDRAWAL STRENGTH

The withdrawal strength of fasteners on the side face of a CLT panel is significantly higher than for fasteners on the narrow side. Because of a few things: material homogenization, the smaller chance that a fastener is inserted in a gap and the side face of the fastener is never inserted parallel to the grain [10].

The withdrawal strength for self-tapping screws can be determined using formula 2.1. This formula is based on a large number of test results [48].

$$F_{ax,a,rk} = \frac{0,35 * d^{0,8} * l_{eff}^{0,9} * \rho_k^{0,75}}{1,5 * \cos^2(\alpha) + \sin^2(\alpha)} \quad (2.1)$$

#### EMBEDMENT STRENGTH

The embedment strength for self-tapping screws can be determined using formula 2.2 and 2.3 for the side face and narrow face respectively. This formula is based on a large number of test results [30].

After the embedment strength of a self-tapping screw connection is calculated, the load-carrying capacity of the connection can be determined with Johnson's formulas for the shear failure modes. Johnson's formulas can be found in Appendix B

$$f_{h,k,perp} = 0,112 * d^{-0,5} * \rho_k^{1,05} \quad (2.2)$$

$$f_{h,k,par} = 0,862 * d^{-0,5} * \rho_{layer,k}^{0,56} \quad (2.3)$$

#### NUMBER OF EFFECTIVE FASTENERS

The resistance of a group of fasteners is dependent on the number of effective fasteners in this group. Fasteners in the side face of the CLT panel which are laterally loaded behave in a ductile manner. This allows for a good distribution of the loads over the group of fasteners. Therefore the number of effective fasteners is assumed to be equal to the total number of fasteners [10].

For fasteners in the narrow face of the CLT panel which are laterally loaded the number of effective fasteners is  $n_{eff} = n^{0,9}$ . In the narrow face splitting already occurs under small deformation. Therefore here a reduction is needed for the number of effective fasteners [10].

For a group of fasteners that are tested for withdrawal the effective number of fasteners is  $n_{eff} = n^{0,9}$ . This is for both the side and narrow face [49].

#### EDGE DISTANCE

To prevent splitting, which is a very brittle type of failure, minimal spacing, edge and end distances are determined. These minimal distances must be taken into account to ensure the load-bearing capacity of the connection. The parameters for the spacing, edge and end distances are shown in figure 2.10. The subscript t is for stressed edge distance and the subscript c is for non-stressed end distance.

Uibel and Blaß tested a large number of fasteners in CLT and came up with values for the minimal spacing, edge and end distances, the distances differ for the side and narrow face and are given in table 2.7.

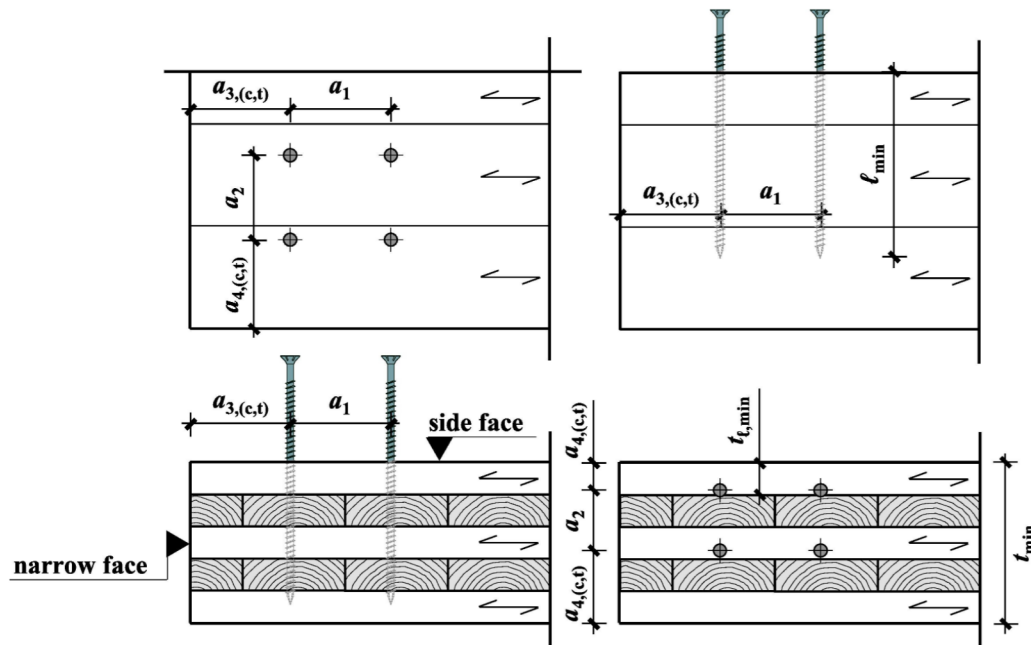


Figure 2.10: The minimal edge distances [10]

Fastener	Position	$a_1$	$a_2$	$a_{3,t}$	$a_{3,c}$	$a_{4,t}$	$a_{4,c}$
Self-tapping	Side face	4d	2,5d	6d	6d	6d	2,5d
	Narrow face	10d	3d	12d	7d	-	5d
Nails	Side face	$(3 + 3 \cos \beta) d$	3d	$(7 + 3 \cos \beta) d$	6d	$(3 + 4 \sin \beta) d$	3d
Dowels	Side face	$(3 + 2 \cos \beta) d$	3d	5d	$4 d \sin \beta$ (min 3 d)	3d	3d
	Narrow face	4d	3d	5d	3d	-	3d

Table 2.7: Minimum spacing, edge and end distance of dowel type fasteners in CLT[30]

### SLIP MODULUS

Connections have a certain stiffness. This stiffness is dependent on the material properties of the CLT and the diameter of the fasteners. The stiffness of a single fastener can be calculated by using the slip modulus  $K_{ser}$ . The slip modulus gives the stiffness per shear plane per fasteners for dowel-type fasteners. The total stiffness of the connection is the number of dowels multiplied by the slip modulus. In equation 2.4 the slip modulus for dowel, screw and bolted type of connections is given. This equation is for the serviceability limit state (SLS).

$$K_{ser} = \rho^{1,5} * d/23 \quad (2.4)$$

In the ultimate limit state (ULS) the slip modulus is only 2/3 of the slip modulus in the SLS. In the ULS there is no longer a linear stress-strain relation. Plastic deformation will occur, this results in a reduced slip modulus.

## 2.2. BASIC PRINCIPLES OF BUILDING ACOUSTICS

Sound is a pressure wave travelling through a medium. This medium can be either a gas, fluid or solid. The pressure is created by a vibrating object, which is also called the sound source. The particles in the medium are brought into vibration by this sound source, this is what creates a pressure wave. When this pressure wave reaches the eardrum of a person the wave is translated into the sounds we perceive [50]. Noise is usually defined as unwanted sounds which disturb the performance of human activities [12]. The definition of acoustical comfort can therefore be defined as:

*'Acoustic comfort is the condition in which a person's activity is not disturbed by the presence of other sounds and no damage occurs to the hearing system. Exposure to noise causes psychological disorder and hinders the performance of normal human activities, reducing efficiency and the ability to concentrate' [12]*

### 2.2.1. QUANTIFICATIONS OF SOUND

The three main characteristics of sound are the sound level, the frequency and the propagation. The sound level can also be defined by the energy level, strength, amplitude or loudness of the sound. The frequency can also be referred to as the pitch or tone. The frequency is dependent on the speed of sound and the wavelength as shown in formula 2.5. The propagation is also described as the path or as the elapsed time.

As said, the amplitude determines the loudness of the sound. The loudness is measured in decibels. Decibels are measured by a logarithmic scale. The wavelength determines the pitch of the sound. Short-wavelength results in high frequencies which are perceived as high notes and long sound waves are perceived as low notes [50].

$$f = \frac{c}{\lambda} \quad (2.5)$$

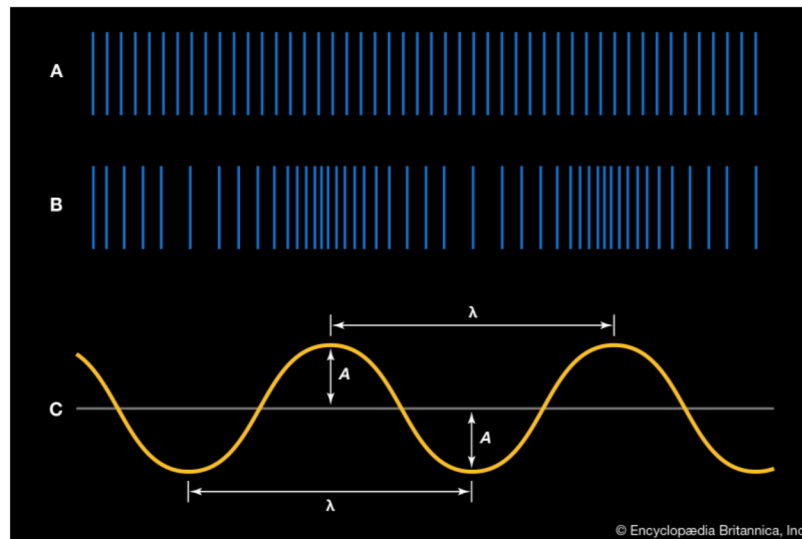


Figure 2.11: Visualization of a sound wave. A - Air without a sound wave, B - compression and rarefaction of the sound wave, C transverse visualization of the sound wave, with the amplitude [A] and wavelength [ $\lambda$ ] [11]



Humans can perceive changes in sound level if the sound reduction or increase is larger than 3 dB. Smaller changes are most likely not noticed by the listener. How humans perceive a change of sound level is shown in table 2.8.

Change in sound level [dB]	Change in perceived loudness
3	Just noticeable
6	Noticeable
10	Double or half as loud
15	Large difference
20	Four times louder or a quarter of the loudness

Table 2.8: Perceived change of loudness with change of the sound level [7]

### 2.2.2. SOUND SOURCES

A distinction is made between two different types of sound sources. Namely, the airborne sound and the impact sound sources. An airborne sound source creates a sound field inside of a room which causes vibration of room separating elements. The room separating elements transmit a part of these vibrations to the air in the adjacent apartments. The most important types of airborne sounds are music, people talking loudly and traffic noises [12]. Impact sounds are sounds that are generated by an impact to a room separating element. This impact causes the element to vibrate, these vibrations are then propagated to the air in the adjacent room where they can be heard. Examples of structure-born sound are the sounds created by the tapping of heels, dragging of furniture, or hammering a nail into a wall [12].

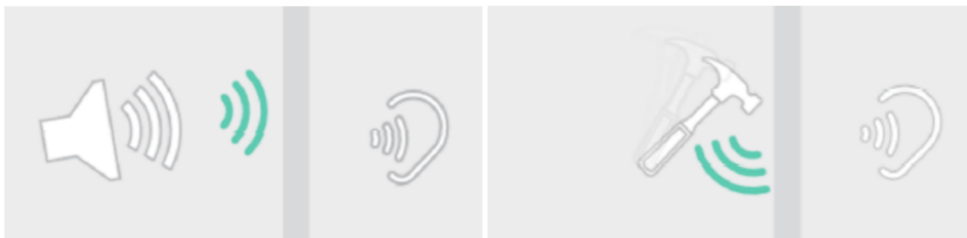


Figure 2.12: Airborne and structure borne sounds sources [12]

Based on these two types of sound sources there are also two types of classifications for sound insulation performance. Namely the airborne sound insulation and the structure-born sound insulation.

### 2.2.3. FREQUENCY RANGE

The frequency of a sound is the number of times that a sound pressure wave repeats itself in one second. The higher the frequency the larger the number of repetitions. The unit used for frequency is hertz [Hz]. The human ear can perceive sounds with a frequency between 20 Hz and 20000 Hz. Because of the geometry of the human ear sounds with a frequency between 500 Hz and 4000 Hz are perceived louder. With equal loudness, a sound with a frequency of 125 Hz is perceived as less loud than a sound with a frequency of 1000 Hz. Therefore the A-weighted decibels [dB(A)] were introduced. In this way, humans decreased sensitivity for lower frequency sound is taken into account [50].

Frequencies above 20000 Hz are also called ultrasound. At the other side of the sound spectrum, there are very low-frequency sounds, which are sounds below 20 Hz. These frequencies are called infrasounds. These very low-frequency sounds can travel much further than high-frequency sounds.

The ISO code describes a calculation model for the frequency bands in the range of 1/3 octave bands 100 Hz to 3150 Hz. It is possible to extend the calculation to 50 Hz if the element and junction data is available [51].

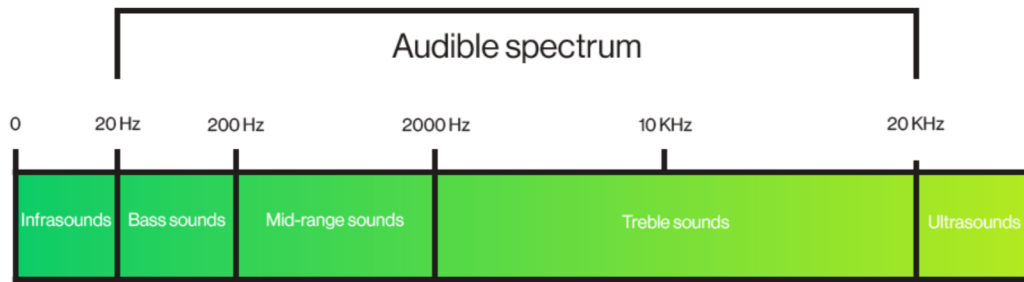


Figure 2.13: Audible sound spectrum 20-20000 Hz [13]

However, the norms given by the 'Bouwbesluit 2012' only take into account the frequency bands from 100 to 3150 Hz. Even though new build lightweight timber buildings meet the same sound insulation requirements as new build heavy concrete buildings the residents of the lightweight timber buildings experience that the sound insulation is insufficient, whilst the residents of heavy concrete buildings are satisfied with the level of sound insulation. The research concluded that frequencies below 100 Hz should also be considered in lightweight buildings, as the low frequencies are of high importance for the evaluation of the sound insulation in lightweight buildings. An extension to the frequency of 20 Hz would improve the correlation between the impact sound reduction index and the residents' acoustical experience for impact sounds. For airborne sound transmission, an extension to 50 Hz is already adequate. Extending the frequency range to 20 Hz showed no further improvement for the correlation between the residents' experience and measured data [43][52]. According to Klas Hasberg and Delphine Bard: "Only considering the lowest frequencies for wooden constructions could give a good overview of the predicted annoyance in the building" [53].

To quickly compare sound transmission through different elements a single number rating was introduced. To get this single value the measured sound curve is compared to a reference curve which is given in ISO 717 [54][55]. This can be done for both airborne and impact sound insulation. The single value is for the 500 Hz frequency. To indicate that a weighted value is given an additional ' $w$ ' is added (e.g.  $R_w$  or  $L_{nT,w}$ ).

The single rated value does not always give the right representation of the acoustic behaviour of an element because for example residential or traffic noise is not taken into account sufficiently. Therefore special spectrum adaption values were introduced.  $C$  for residential noise,  $C_{tr}$  for traffic noise and  $C_I$  for impact walking noises [54][55].

#### 2.2.4. SOUND ABSORPTION, REFLECTION AND TRANSMISSION

When a sound wave hits a surface the wave will be partly reflected, absorbed and transmitted, as shown in figure 2.14. So there is a difference between sound absorption and sound insulation. The absorption is the amount of energy of a sound wave taken by the element. In this way, the sound power in the room of the sound source will decrease. Whilst the sound insulation ensures that the amount of sound which is transmitted to an adjacent room will be limited [12]. For this research, the goal is to reduce the amount of sound transmission. The amount of incidental energy is equal to the amount of energy reflected, absorbed and transmitted altogether.



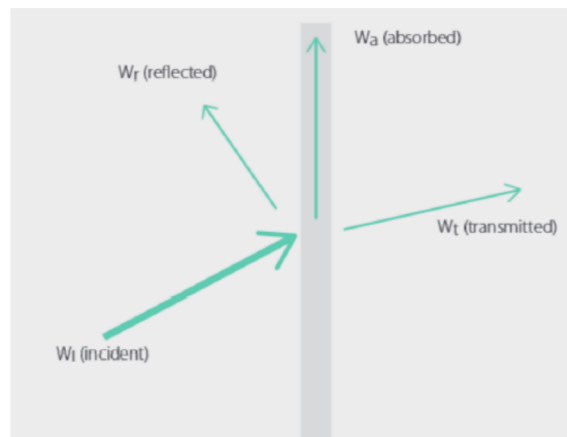


Figure 2.14: Absorption, reflection and transmission of a sound wave[12]

### INTERNAL DAMPING

The internal damping of mass timber is high compared to concrete. For CLT elements the loss factor is higher than 0,03 for all frequencies below 2000 Hz, as can be seen in figure 2.15. The ISO standard states that if the internal loss factor is 0,03 or higher the effect of the edge losses can be neglected [56]. In the low-frequency range, the internal damping of a CLT element is in the range of 0,04-0,08. For concrete the internal damping is in the range of 0,006 [14].

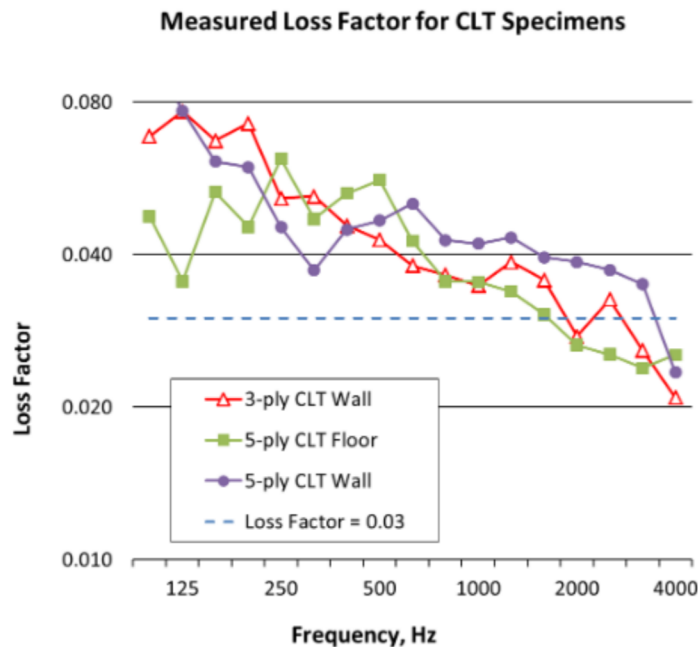


Figure 2.15: Measured internal loss factors of CLT elements [14]

### ACOUSTIC IMPEDANCE

The impedance governs the efficiency of the sound wave transmission at the boundary between two different media. The specific acoustic impedance ( $Z$ ) is a relation between the speed of sound and the density of the medium. If the difference in acoustic impedance at the boundary is large then most of the sound waves will be reflected. If the difference in acoustic impedance is small then most of the sound waves will be transmitted.

$$Z = \rho * c \quad (2.6)$$

### 2.2.5. WAVE PROPAGATION IN SOLIDS

There are three different types of waves: the compression longitudinal wave, the shear wave and the bending wave. In gasses and fluids, only the compression longitudinal waves can be transferred. Solids can also transfer shear waves and bending waves.

#### QUASI LONGITUDINAL WAVES

Quasi longitudinal waves or compression longitudinal waves can travel through air, fluids and solids. Compression waves can occur in solid elements only when the dimensions of the elements are larger than the wavelength of the compression wave. For direct sound transmission, the compression waves are usually not important, as the structural elements are usually thin compared to the wavelengths.

For the transmission of structure-borne sounds, compression waves are significant and have to be taken into account. The quasi longitudinal waves can be generated in the junction by bending waves in the connecting element. This wave does not only propagate in-plane in the x-direction but also out-of-plane in the y- and z-direction.  $\xi$  gives the term for the longitudinal strain and  $\zeta$  and  $\eta$  for the y- and z-directions respectively. The lateral strains produce small displacements and therefore quasi-longitudinal waves are usually insignificant when compared to the influence of bending waves. [15].

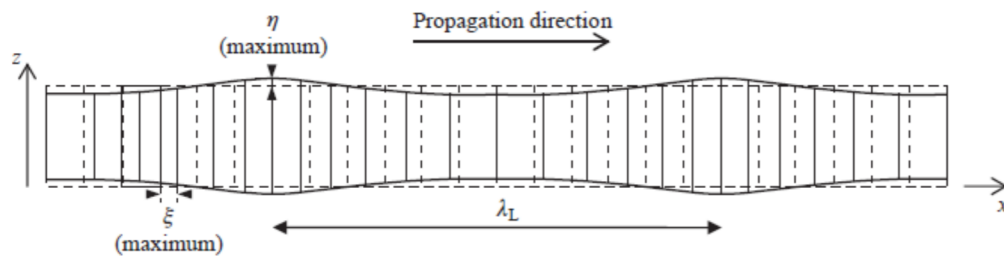


Figure 2.16: Quasi-longitudinal wave [15]

#### SHEAR WAVES

Shear waves can only be transferred in solids since solid elements can support the shear stresses. The propagation in the x-direction is the same as for compression waves, but the in-plane displacement is now in the y-direction. These waves can only be excited by structure-borne sound sources. For airborne sound sources, the element can only be excited in the direction tangential to the air in the room, so this will not result in a shear wave [15].

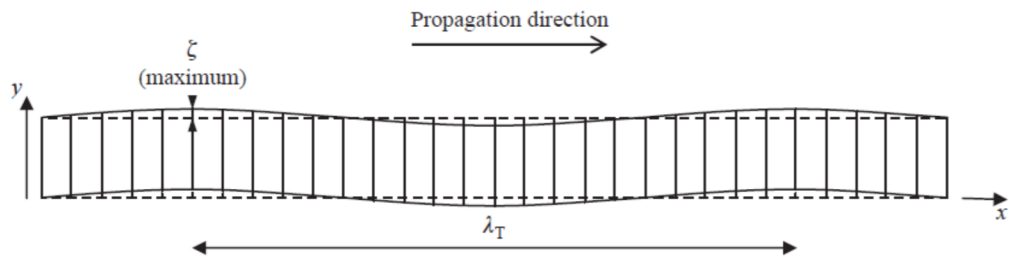


Figure 2.17: Shear wave [15]

#### BENDING WAVES

Bending waves oscillate perpendicular to the travel direction of the wave, the wave causes both rotations and lateral displacements. Compared to the in-plane waves created by compression and shear waves the bending waves play a larger contribution to the radiation of sound [15]. For both the airborne and structure-borne sound transmission, the bending waves are of the most importance.

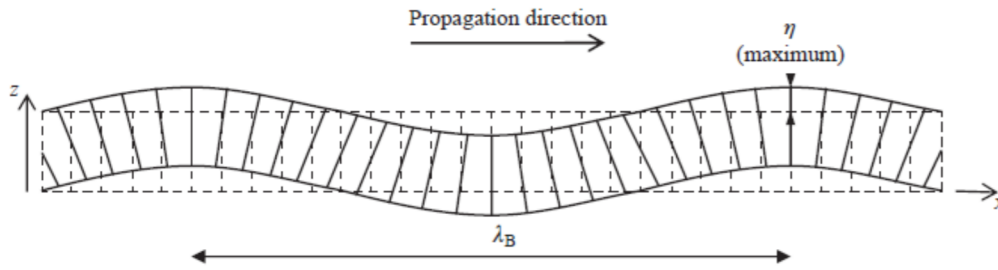


Figure 2.18: Bending wave [15]

The wave speed depends on the medium in which the wave is travelling. For building acoustics, the temperature is usually assumed to be 20 °C in this way the density of the medium is assumed to be a constant value. The speed of a sound wave travelling through air is 343 m/s. For CLT the speed of sound is between 3000-5000 m/s depending on the wood properties.

$$c = \sqrt{\frac{K}{\rho}} \quad (2.7)$$

### 2.2.6. AIRBORNE SOUND INSULATION

The airborne sound transmission between two adjacent rooms can travel through different paths. The direct sound transmission travels directly through the room separating elements. The flanking sound paths are all the other possible transmission paths. The direct and flanking sound paths can go horizontal or vertical. For each junction there are three different flanking paths, for a room with four junctions this results in twelve possible flanking paths. The horizontal paths through the top junction are shown in figure 2.19. The total sound reduction between two apartments depends on both the direct sound reduction and the flanking sound reduction. So to improve the total sound reduction it is important to reduce both types of sound transmission.

It is important to mention that higher-order flanking paths also exist. This is for example a flanking path where the sound travels through more than one junction. For wooden elements, the internal losses are higher than the losses at the surface. So, more sound energy is converted into heat inside the wood element than at the surface where the energy is transmitted to other surfaces [57]. Therefore only the first-order flanking paths will be investigated for this research because the high internal damping of the CLT elements makes the higher-order flanking paths insignificant.

For airborne sounds, the first-order flanking paths are different for apartments next to each other or below each other. The different paths are shown in figure 2.19 & 2.20.

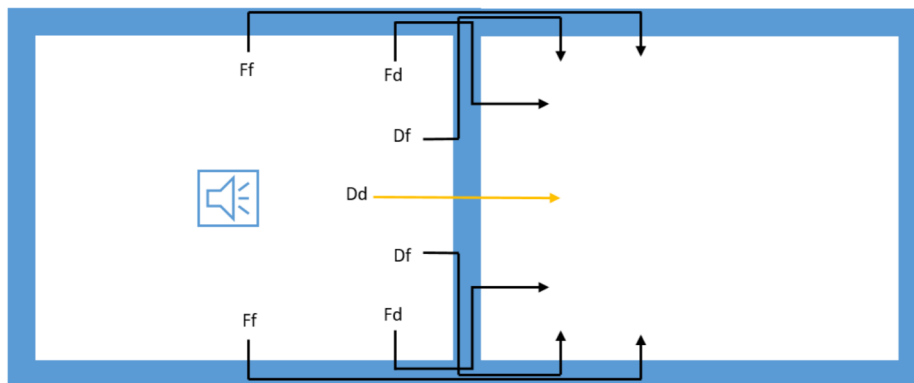


Figure 2.19: Horizontal sound transmission paths for airborne sounds

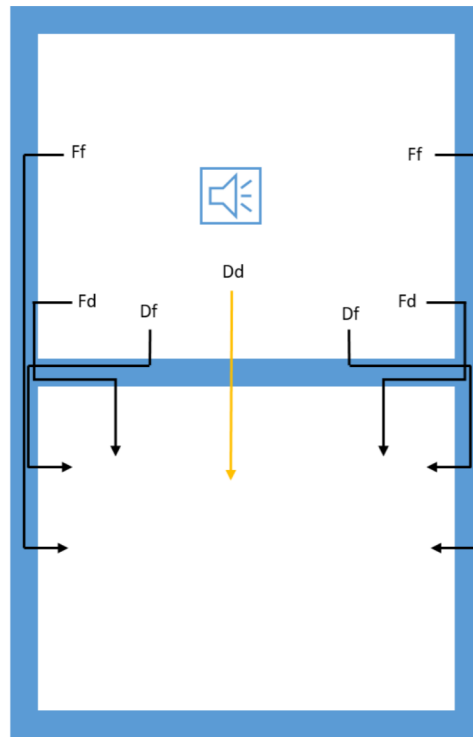


Figure 2.20: Vertical sound transmission paths for airborne sounds

The most dominant transmission path depends on the design of the junction [57]. Research shows that the sound insulation is the lowest when the floor is a continuous element. The floor-to-floor flanking transmission is in this case the most dominant flanking path. By applying a topping to the floors, the floor-to-floor flanking is significantly lower but still significant. The most dominant flanking path is in this case no longer the floor to floor path but the wall to floor flanking path. This shows that there is not one dominant flanking path since this depends on the design of the junction. This means that to design an acoustically efficient junction an iterative process is required [57].

The transmission path with the lowest sound reduction index is the dominant path. By improving the sound reduction of this dominant path the total sound reduction will be reduced most significantly. For the direct sound transmission index companies like Rothoblaas, Stora Enso and Dataholtz executed a large number of tests for different floor and wall build-ups. The flanking paths are less investigated but these same companies also tested a couple of junction configurations.

The ISO 12354 gives a standard on how to predict the airborne and contact sound transmission between two apartments. This method is based on the acoustic performance of the building elements involved and the connection between the elements. The airborne sound insulation can be calculated primarily by using empirical data. The calculation method is for heavy building materials. But the code also provides additional details to apply it to lightweight constructions like CLT [58][51]. The estimation of the airborne sound insulation is possible by predicting the apparent sound reduction ( $R'$ ). For the apparent sound reduction, direct and flanking sound transmission is included. The ISO 12354-1 provides a calculation model to estimate the airborne sound reduction between rooms. The code makes a difference between type A and type B elements. Type A elements have a structural reverberation time which mainly depends on the connected elements, such as concrete, glass, metal and solid woods including CLT. Type B elements are elements for which the structural reverberation time does not depend on the connected elements, an example is plasterboard cladding on a timber or metal frame.

The code gives two methods to calculate the airborne sound insulation. The simplified method requires weighted values as input data and a more detailed calculation which requires spectral values for all the involved elements. The calculation methods will be discussed in more depth in section 2.3.1. Both methods are based upon the same general principle where the sound power in the receiving room is calculated with the different transmission factors by the following formula:

$$\tau' = \tau_d + \sum_{f=1}^n \tau_f + \sum_{e=1}^m \tau_e + \sum_{s=1}^k \tau_s \quad (2.8)$$

The first two terms are the direct and flanking sound transmission. The flanking sound transmission of the three first-order flanking paths (Df, Fd and Ff) of the four elements surrounding the separating element are summed. The third term is also related to the direct sound transmission but related to the separating element normalized level difference. The fourth term is dependent on the total indirect sound transmission. The amount of sound transmission by this term is highly dependent on the degree of accuracy in the workmanship, as small gaps which are not properly taped or covered can cause major sound leaks. This term is highly variable and therefore the code does not give a standard formula on how to predict the indirect sound transmission. Therefore this term will not be included in the calculations. The possible additional sound transmission by indirect sound transmission is something to keep in mind.

### 2.2.7. IMPACT SOUND INSULATION

Impact sound, or structure-borne sounds, are sounds generated by an impact. The impact sound transmission between two adjacent rooms can travel through different paths. For impact sounds the first order flanking paths are different for apartments next to each other or below each other. The different paths are shown in figure 2.21 & 2.22. For rooms next to each other, there are only two flanking paths (Ff and Fd). For rooms on top of each other, there are four direct-flanking paths, one for each wall (Df). The ISO 12354-2 provides a calculation model to estimate the impact sound reduction between rooms. Similar to the code for airborne sound transmission there is a simple and detailed calculation method. With the need for weighted values for the simple method and spectral values for the detailed method. These calculation methods will be explained in section 2.3.1.

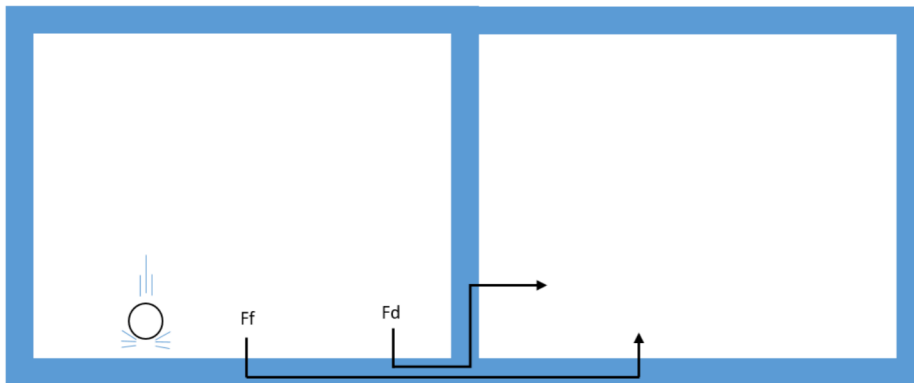


Figure 2.21: Horizontal sound transmission paths for impact sounds

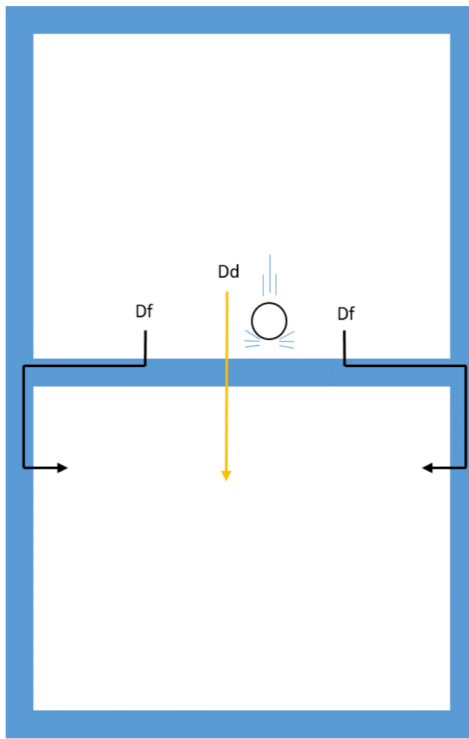


Figure 2.22: Vertical sound transmission paths for impact sounds

### 2.3. BUILDING CODES FOR SOUND INSULATION

There are different rules and regulations when it comes to the level of sound insulation required for new residential buildings. This is to check whether the sound insulation of a new building will be sufficient. With CLT being a lightweight building material the user experience differs from the experience in residential buildings built with traditional materials. Therefore it might be needed to set additional requirements for the sound insulation of CLT buildings, especially for the low-frequency sounds.

In the Netherlands, new buildings should meet the requirements set by the building codes. The official code is the 'Bouwbesluit 2012' [59]. The acoustic requirements in the 'Bouwbesluit 2012' are according to the NEN 1070 [31]. Here there are five different quality levels (k1 to k5). Where k1 is the highest level of quality, k3 is the quality level required by the 'Bouwbesluit 2012', and k5 is the minimal level that is applicable when buildings are renovated. In practice levels k4 and k5 are rarely used. The regulations for airborne and structure-borne sound insulation for residential buildings are defined by two single-valued quantities. The quantities  $D_{nT;A}$  and  $L_{nT;A}$  form the basis for quantifying the sound insulation.  $D_{nT;A}$  is the A-weighted normalized airborne sound reduction and the  $L_{nT;A}$  is the A-weighted normalized contact sound level. Both quantities are expressed in dB(A). These two quantities summarize the sound transmittance of both the direct and the flanking sound transmittance [31]. The requirements according to the NEN 1070 are given in table 2.9. These are the values for the maximal sound transmission into a living space from a sound source outside the house. For the sound transmission to non-living spaces or the transmission between rooms inside the same house the requirements are lower.

Quality level	Airborne sound reduction [dB(A)]	Impact sound reduction [dB(A)]
k1	$D_{nT;A} \geq 62$	$L_{nT;A} \leq 43$
k2	$D_{nT;A} \geq 57$	$L_{nT;A} \leq 48$
k3	$D_{nT;A} \geq 52$	$L_{nT;A} \leq 53$
k4	$D_{nT;A} \geq 47$	$L_{nT;A} \leq 58$
k5	$D_{nT;A} \geq 42$	$L_{nT;A} \leq 63$

Table 2.9: Requirements for a living space in a residential building with a sound source outside the house [31]

For this research, the requirements for multilayered residential buildings are of importance. The requirements for multilayered residential buildings are the highest standards given in the code. The 'Bouwbesluit 2012' states that the  $D_{nT;A;k}$  should be larger or equal to 52 dB from an accommodation area to a residential room. For the  $L_{nT;A;k}$  the requirement is that the sound level is below 54 dB from an accommodation area to a residential room. Important is to notice that the 'Bouwbesluit 2012' uses the characteristic terms. To get the characteristic terms from the A-weighted normalized airborne sound reduction and the A-weighted normalized contact sound level the following formulas from the NEN 5077 can be used:

$$D_{nT;A;k} = D_{nT;A} - 10 \log\left(\frac{0,16S}{T_0S}\right) \quad (2.9)$$

$$L_{nT;i} = L_i - 10 \log\left(\frac{T_i}{T_0}\right) \quad (2.10)$$

$$L_{nT;A;k} = \sum_{i=100}^{500} 10 \frac{L_{nT;i}}{10} - 15 \quad (2.11)$$



### 2.3.1. SOUND TRANSMISSION ACCORDING TO THE ISO 12354

This section focuses on the sound transmission calculation method provided by the ISO 12354 part 1 and 2. The two codes describe both the simplified and detailed calculation methods for the airborne and impact sound transmission between apartments. Here the calculation steps are described. As well as the few modifications which were made to make the calculation method applicable for CLT constructions. Based on these formulas an Excel sheet was built to calculate the airborne sound transmission between the apartments for different junction configurations.

#### DIFFERENCES HEAVY HOMOGENEOUS BUILDING ELEMENTS AND CLT

CLT elements have a lower mass and a higher internal loss factor compared to heavy homogeneous elements, such as concrete. When using the calculation method composed in the NEN-EN 12354 for CLT elements a few modifications are needed. There are five modifications needed when using the ISO code for CLT constructions [26]:

- CLT elements have a high internal loss factor. The internal loss factor is in the range of 0,03 or higher whilst for solid concrete, this factor is in the range of 0,006. Because of these high internal losses, the direct sound transmission measured in a lab and in-situ is assumed to be equal. In the low-frequency, the internal loss factor is 0,08.
- The critical resonance frequency for CLT is higher compared to concrete. For concrete, the critical frequency is below the frequency range of interest whilst for CLT this frequency is in the area of interest for acoustics. For a 3-ply element, this frequency is around 400 Hz. A correction for the sound transmission loss measured in a lab is recommended below the critical frequency.
- The improvements by additional linings are different for CLT elements. The mass of the CLT element is closer to the mass of the additional lining and therefore the sound reduction effect is different than for concrete elements. So, the measurement executed on concrete elements can not be used for CLT constructions. Therefore measurements on CLT elements are needed. A large number of measurements have been done by different companies or can be obtained with an acoustic program like INSUL.
- The vibration reduction index in the code is based on elements that are continuously and rigidly connected. For CLT elements the number of connectors and the type of connector play a large role in the vibration reduction index. Rothoblaas has measured the vibration reduction index for a large number of different connector types. The type and number of connectors have a large influence on the vibration reduction index.
- For CLT elements the equivalent absorption length is set equal to the surface area of the element because of the high internal losses of a CLT element.

#### AIRBORNE SOUND TRANSMISSION - SIMPLIFIED CALCULATION METHOD

The ISO code [56] gives a simplified formula for the total sound reduction between two adjacent rooms. For this method, only weighted input values are needed. How to get to the weighted value is described in the ISO 717-1.

$$R'_w = -10 \log[10^{-R_{Dd,w}/10}] + \sum_{F=f=1}^n 10^{-R_{Ff,w}/10} + \sum_{f=1}^n 10^{-R_{Df,w}/10} + \sum_{F=1}^n 10^{-R_{Fd,w}/10}$$

In the ISO code, there is included a term which includes the sound transmission through small technical elements. For the sake of simplicity, this term is left out in this research. It is important to keep in mind this additional sound transmission.

The direct sound transmission is the sound transmission through the room separating element. The weighted direct sound reduction can be approximated by using the following formula:

$$R_{Dd,w} = R_{D,w} + \Delta R_{Dd,w}$$

with:

$R_{Dd,w}$  = weighted sound reduction index of the separating element [dB]

$\Delta R_{Dd,w}$  = improvement of the total weighted sound reduction index by additional lining [dB]



For the sound transmission through the flanking paths there is a different formula. Here there are additional terms as the sound travels through different elements and the junction. The weighted flanking sound reduction indices  $R_{ij,w}$  can be approximated by using the following formulas:

$$R_{Df,w} = \frac{R_{D,w} + R_{f,w}}{2} + \Delta R_{Df,w} + K_{Df} + 10 * \log\left(\frac{S_s}{l_0 l_f}\right)$$

$$R_{Ff,w} = \frac{R_{F,w} + R_{f,w}}{2} + \Delta R_{Ff,w} + K_{Ff} + 10 * \log\left(\frac{S_s}{l_0 l_f}\right)$$

$$R_{Fd,w} = \frac{R_{F,w} + R_{d,w}}{2} + \Delta R_{Fd,w} + K_{Fd} + 10 * \log\left(\frac{S_s}{l_0 l_f}\right)$$

#### AIRBORNE SOUND TRANSMISSION - DETAILED CALCULATION METHOD

The following subsection will explain the detailed calculation method. Here also the above-mentioned parameters will be explained further. The detailed calculation model can be used for each frequency domain. So for this calculation spectral values are needed and not weighted values. For this method, the 1/3 octave bands are used. Due to the frequency dependency of each parameter, a larger number of calculations is needed. Formula 2.12 is used to calculate the apparent sound reduction between two apartments. It is an accumulation of the direct sound transmission and the sound transmission through the 12 first-order flanking paths.

$$R' = -10 \log[10^{-R_{Dd}/10}] + \sum_{F=f=1}^n 10^{-R_{Ff}/10} + \sum_{f=1}^n 10^{-R_{Df}/10} + \sum_{F=1}^n 10^{-R_{Fd}/10} \quad (2.12)$$

The flanking sound reduction indices  $R_{ij}$  can be approximated by using the following formulas:

$$R_{Df} = \frac{R_{D,situ} + R_{f,situ}}{2} + \Delta R_{D,situ} + \Delta R_{f,situ} + D_{v,Df,situ} + 10 * \log\left(\frac{S_s}{l_0 l_f}\right) \quad (2.13)$$

$$R_{Ff} = \frac{R_{F,situ} + R_{f,situ}}{2} + \Delta R_{F,situ} + \Delta R_{f,situ} + D_{v,Ff,situ} + 10 * \log\left(\frac{S_s}{l_0 l_f}\right) \quad (2.14)$$

$$R_{Fd} = \frac{R_{F,situ} + R_{d,situ}}{2} + \Delta R_{F,situ} + \Delta R_{f,situ} + D_{v,Fd,situ} + 10 * \log\left(\frac{S_s}{l_0 l_f}\right) \quad (2.15)$$

There is a formula given in the ISO 12354-1 which corrects the sound reduction lab values to in-situ values. This correction is needed for heavy-weight constructions since the structural reverberation time is different for lab and in-situ situations. Research shows that for elements with a high internal loss factor, such as CLT, the structural losses for lab and in-situ situations are the same. Therefore it is safe to assume that the lab and in-situ values are similar for CLT elements [60].

#### VIBRATION REDUCTION INDEX

$D_{v,ij,situ}$  is called the direction averaged in-situ junction velocity level differences. This parameter depends on the  $K_{ij}$  and the in-situ equivalent absorption length. These two parameters are explained in the section 3.2. The other parameters are similar to the parameters used for the simple calculation method except for the in-situ adaptations. The formula for the direction averaged in-situ junction velocity level differences is 2.16. If the value is below zero, zero is taken as the velocity level difference. As this is in practice not possible.

CLT is classified as a type A element in the ISO code. But there is one major difference between CLT elements and other types of A elements. CLT elements are only connected at a number of points, whereas other types of A elements have a monolithic line connected joints.

Annex F of the EN 12354-1 gives formulas that predict the vibration reduction indices for CLT junctions, see figure 2.23. The formulas are based on empirical data which were obtained by measuring in a few buildings. Found was that the vibration reduction index highly depend on the frequency.

$$D_{v,ij,situ} = K_{ij} - 10 \log\left(\frac{l_{ij}}{\sqrt{a_{i,situ} a_{j,situ}}}\right) \quad (2.16)$$

The formulas for the vibration reduction indices for T and X junctions can be found in figure 2.23.

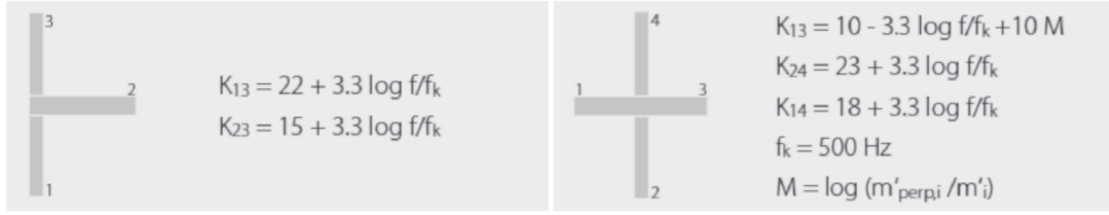


Figure 2.23: Vibration reduction index for CLT T and X junctions according to ISO 12354-1 [12]

The vibration reduction index in the ISO code only depends on the frequency. But as stated in section 3.2, the vibration reduction index does not only depend on the frequency but also other parameters. Examples of important parameters are the type of connectors, the number of connectors, and the presence or absence of a resilient interlayer between the connected CLT elements.

#### IMPROVEMENTS BY ADDITIONAL LINING

The ISO 12354-1 does not include a formula to calculate the additional airborne sound reduction for additional linings with respect to the frequency. Therefore it is suggested to use the formula in the ISO 12354-2 for the impact sound reduction by additional lining. So the rough assumption is made that  $\Delta L = \Delta R$ .

For floating elements made of sand/cement or calcium sulfate the additional sound reduction can be calculated with the following formula:

$$\Delta L = \Delta R = 30 * \log\left(\frac{f}{f_0}\right) \quad (2.17)$$

For dry floating constructions the formula is changed to:

$$\Delta L = \Delta R = 40 * \log\left(\frac{f}{f_0}\right) \quad (2.18)$$

with  $f_0$  for additional linings on elastic layers:

$$f_0 = \frac{1}{2\pi} * \sqrt{s' * \left(\frac{1}{m'_1} + \frac{1}{m'_2}\right)} \quad (2.19)$$

or  $f_0$  for additional lining with metal or wooden studs or battens and a cavity filled with a porous insulation layer:

$$f_0 = \frac{1}{2\pi} * \sqrt{\frac{111}{d} * \left(\frac{1}{m'_1} + \frac{1}{m'_2}\right)} \quad (2.20)$$

The ISO code states that if this approach is used the total sound reduction is the total of the maximal additional sound reduction and 50% of the minimal additional sound reduction.

$$\Delta R_{ij} = \text{MAX}(\Delta R_i + \Delta R_j / 2; \Delta R_i / 2 + \Delta R_j) \quad (2.21)$$

As the ISO code already states itself, these formulas result in rough estimations of the additional sound insulation. Also, it is not possible to calculate the values for build-ups which consist of multiple layers. Other options to obtain these values are measurements or the use of acoustic sound insulation programs (for example INSUL).

### IMPACT SOUND TRANSMISSION

For the calculation of the impact sound transmission, a large number of formulas and parameters is similar to the calculation method for airborne sound transmission. For impact sound insulation the calculation method is different for apartments next to each other and above each other. This is because the flanking paths involved are different in these situations.

The total impact sound pressure level difference between two rooms next to each other can be calculated by using the formula 2.22. As said there are two flanking paths: floor-wall (Fd) and floor-floor (Ff). There is no direct sound transmission in this case.

$$L'_n = 10 * \log\left(\sum_{j=1}^n 10^{\frac{L_{n,ij}}{10}}\right) \quad (2.22)$$

The total impact sound pressure level difference between two rooms on top of each other can be calculated with formula 2.23. For this case, there is direct sound transmission involved as well as the transmission of the four walls connected to the floor.

$$L'_n = 10 * \log\left(10^{\frac{L_{n,d}}{10}} + \sum_{j=1}^n 10^{\frac{L_{n,ij}}{10}}\right) \quad (2.23)$$

### DIRECT IMPACT SOUND TRANSMISSION

The formula for the direct impact sound transmission is given in equation 2.24. The values are obtained by the measured normalized impact sound pressure level minus the effect by additional linings. The same equation can be used with single number values. Then the weighted values must be used instead of the spectral values.

$$L_{n,d} = L_{n,situ} - \Delta L_{situ} - \Delta L_{d,situ} \quad (2.24)$$

When there are no measurements available for the impact sound pressure level the ISO 12354-2 states that sound reduction improvement values can be used instead.

### FLANKING IMPACT SOUND TRANSMISSION

The general formula for the flanking sound is similar for airborne and structure-born sound. Three new parameters are the normalized impact sound pressure level, the in-situ normalized impact sound, and the impact sound reduction by an additional layer.

$$L_{ij} = L_{n,situ} - \Delta L_{situ} + \frac{R_{i,situ} + R_{j,situ}}{2} - \Delta R_{j,situ} - D_{v,ij,situ} - 10 * \log\left(\frac{S_i}{S_j}\right) \quad (2.25)$$

The building codes set a minimum level of requirement for the standardized impact sound pressure level. This level is dependent on the normalized impact level but also on the dimensions of the dwelling. How to get the value is shown in the equation below.

$$L'_{nT} = L'_n - \left(10 * \log\left(\frac{0,16V}{A_0 T_0}\right)\right) \quad (2.26)$$

## 2.4. CONCLUSION

The literature review touched upon building with the material cross-laminated timber, the basic principles of sound and the building codes concerning sound transmission. The knowledge gained in this chapter is of importance for the design assumptions and constraints of the numerical sound transmission models.

Timber is an orthotropic material with different material properties in the x, y and z-direction. CLT elements are assembled out of several timber lamellas where the grain direction of lamellas is alternating. The lamellas are glued together under high pressure, this creates a solid panel. The density of the panel is not influenced by the type of glue. It is assumed that the panels are fully bonded. A higher number of layers will result in an element that acts more as an isotropic material since the bending stiffness of the primary axes become more equal. For apartment buildings up to five stories, the most common construction system is the platform type of construction. The connection between the panels is created with a number of connectors. Common connectors are screws, angle brackets and hold-downs.

To quantify the amount of sound transmission it is important to quantify the number of decibels a person can perceive and in which frequency range. Sounds are pressure waves created by a vibrating sound source. The sound waves can travel both through the air and construction. When the level of sound disturbs the performance of human activities it can annoy the residents. The loudness of sound is measured in decibels, decibels are measured on a logarithmic scale. An increase of 10 dB means doubling the loudness. An increase of 5 dB is noticeable for a person and can make the difference between an acceptable level of sound transmission and annoyance. An increase of 3 dB is almost not noticeable for a person. So, to give an acceptable estimation of the sound reduction of an element, it should be within the range of 3 dB.

Humans can perceive sounds in the frequency range 20 to 20000 Hz. To quickly compare different the sound reduction of different elements a single weighted value is used. The value is based on the sound transmission in the 1/3 octave bands 100-3150 Hz. The low-frequency sound transmission is the main cause of annoyance in lightweight buildings. For airborne sound transmission in lightweight buildings, an extension to 50 Hz would lead to more accurate results. For impact sound transmission the extension should be up to 20 Hz.

The total sound reduction between two apartments depends on both the direct sound reduction and the flanking sound reduction. To improve the total sound reduction it is important to reduce both types of sound transmission. The total amount of airborne sound reduction between two apartments must be 52 dB(A) or higher. To predict the flanking sound transmission from element i to j the direct sound transmission through elements i and j are needed as well as the vibration reduction index between element i and j.

# 3

## SOUND REDUCING MEASURES

The goal of this chapter is to give insight into the different types of sound-reducing measures and the effect they have on the amount of sound transmission between rooms. To answer the sub-question: 'What measures affect the total amount of sound transmission between rooms in cross-laminated timber buildings?'. The second sub-question that will be answered in this chapter is: 'What is the measured effect of different sound-reducing measures?'. The measurement data collected from the literature will also be used to verify the numerical sound transmission models. An interview with the acoustical advisor of the HAUT project gave additional insights into the design process for the acoustics in a CLT building and sound-reducing measures used in practice. The main findings of the interview are given in appendix A. The sound transmission from the source room to the receiver room can be determined by five different factors in the transmission path [16]:

- The efficiency of the sound injection into the surface element in the sending room, either by the airborne or impact source
- The attenuation of the sound from the point of injection to the junction
- The attenuation through the junction
- The attenuation from the junction to the point where the sounds enter the receiver room
- The efficiency of the radiation from the structural element to the receiver room

So there are three sources of attenuation between the sound source and the receiver, as can be seen in figure 3.1.

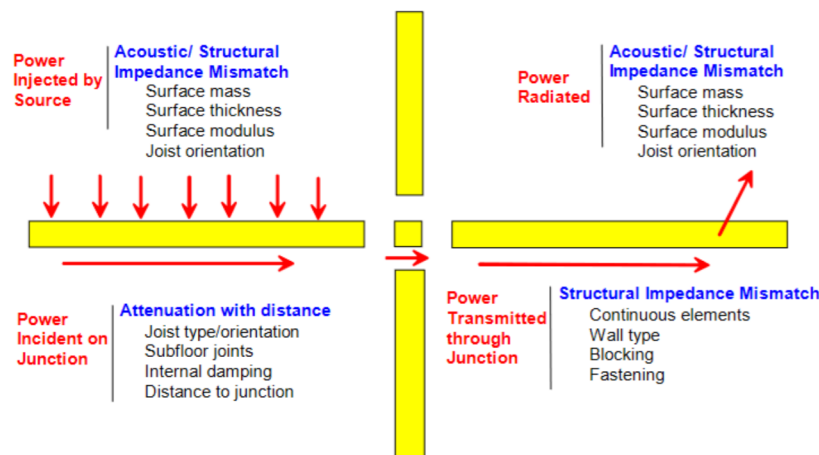


Figure 3.1: Diagram showing the factors for flanking transmission [16]

### 3.1. SINGLE LEAF ELEMENT

The sound reduction of an element always varies over the frequency range. Experiments show that the frequency spectrum can be divided into three different regions. The first region is the region below the resonance frequency. Here the sound reduction is mainly influenced by the stiffness of the element. In this region, the length of the sound wave is much larger than the thickness of the element. This is called the stiffness controlled region.

The second region is mass controlled. For this region, the mass law applies. This means that doubling the mass will lead to an additional 6 dB sound reduction by the element [11]. This region is after the first-panel resonance frequency and before the coincidence region.

The third region is the coincidence-controlled region. Here the wavelength of the panel coincides with the wavelength of the sound wave. The result is that these waves start to vibrate coincidentally, which leads to a dip in the sound insulation. The coincidence region of a CLT element lies within the frequency spectrum which is relevant for building acoustics. Also due to the orthotropic behaviour of CLT this region is wider for CLT elements than for concrete. Because the different layers of the element have different coincidence-induced sound insulation dips. The region depends on the ratio of the stiffness of the different layers. This stiffness depends on the thickness and arrangement of the lamellas. The region can be a few third-octave bands or even a few octave bands[17].

The coincidence frequency for 3-ply elements is around 400 Hz. For 5-ply elements, this value is lower and around 300 Hz. For 7-ply elements this value is around 200 Hz [18]. The dips are not that obvious, this is due to the high internal damping of CLT and because there are multiple dips and not one because CLT is an orthotropic material.

At the higher frequencies, a dip is expected due to the thickness resonance. For 3-ply, 5-ply, and 7-ply this dip is around 2000 Hz, 4000 Hz, and 6000 Hz respectively [18]. Only for thin CLT elements, this dip will be in the frequency range of interest.

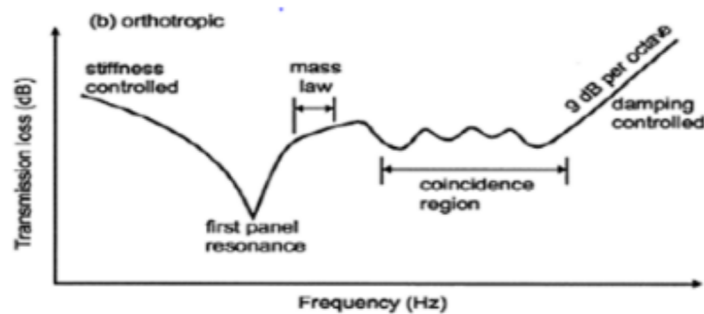


Figure 3.2: Transmission loss for orthotropic materials[17]

The sound insulation capacity for bare CLT elements depends on the thickness of the element. In the figure below measured data is shown for various thicknesses. Figure 3.3 shows the sound reduction index for several different bare CLT elements. For a thickness of 175 mm the weighted sound reduction is 41 dB, for 140 mm this is 37 dB, and for 78 mm this value is 33 dB. The weighted sound reduction index gets higher for a thicker element, this is in line with the mass law. The type of wood, type of glue, and the manufacturing process is also of influence. Figure 3.4 show the measurement values for three bare CLT panels. The three panels are all 5-ply elements with a thickness of 175 mm. The measurement values are slightly different, usually within the range of 4 dB. Only around the coincidence frequency (300 Hz) and the resonance frequency (4000 Hz) do the differences show a larger variation.



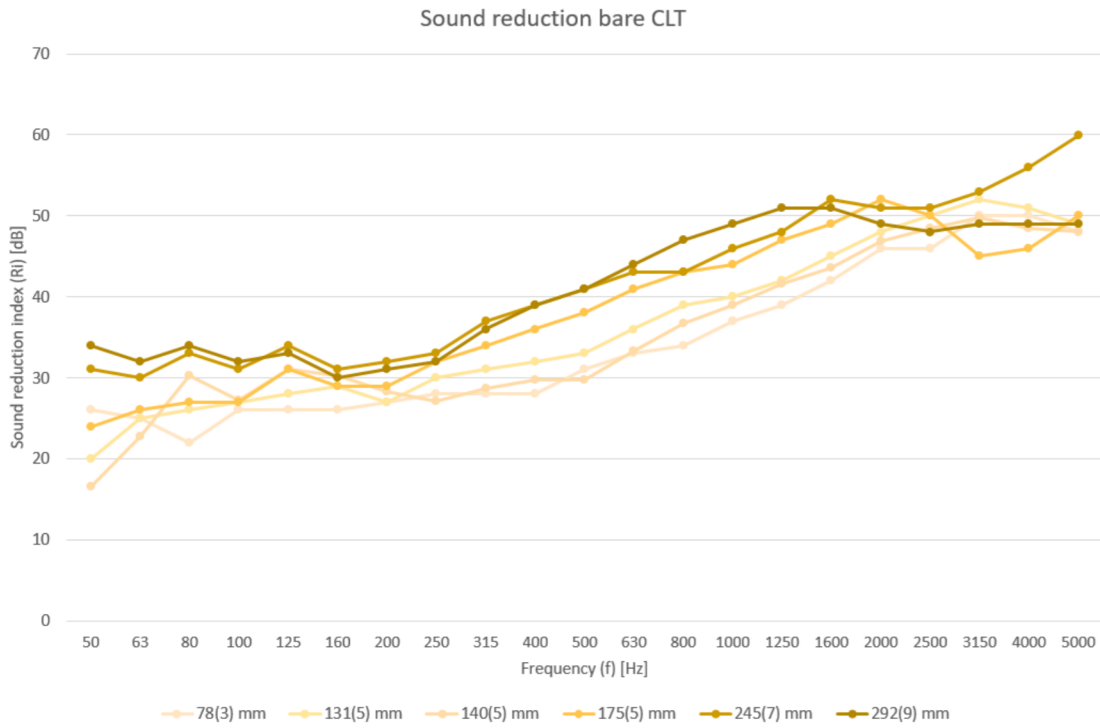


Figure 3.3: Measurement values of the sound reduction index for different thicknesses [18] [19]

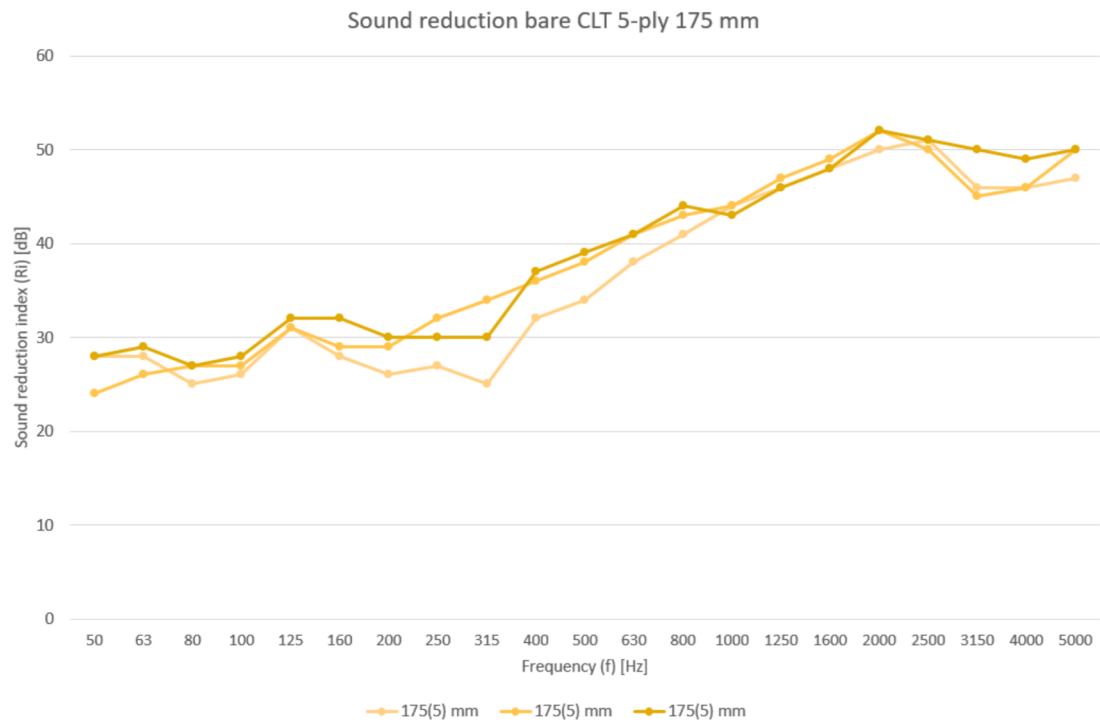


Figure 3.4: Measurement values of the sound reduction index for three 5-ply panels with a thickness of 175 mm [18] [19]

## DOUBLE-LEAF ELEMENT

Double-leaf elements are elements that consist of two CLT panels with a cavity in between. This cavity is either filled with air or a sound-reducing material. For double-leaf elements, the sound reduction is different than for single-leaf elements. The effect of additional lining on double leaf elements is different than on single leaf elements. There will be a dip around the mass-air-mass resonance frequency. The frequency where this dip occurs depends on the thickness of the two CLT elements, the width of the cavity, and the filling of the cavity. For example, for two 78 mm 3-ply elements with an air cavity of 25 mm this will be around the 63 Hz frequency. At the resonance frequency of the single panels, there will also be a dip. If the panels have the same thickness the dip will be larger [18].

### 3.2. VIBRATION REDUCTION INDEX

The vibration reduction index is a very important parameter for the determination of flanking sound transmission. The vibration reduction index determines how much energy can be transmitted through a junction. This index depends on the structural coupling of the elements. A high index results in a large reduction of the flanking sound transmission.

The NEN-EN-ISO 10848:2017[58] gives measurement techniques on how to validate the flanking sound transmission of one or more building components. These measurements take place in a laboratory or on-site. Where the performance of one element or connected elements can be expressed in either the normalized flanking level difference, the normalized flanking impact sound pressure level, or the vibration reduction index of a junction.

The flanksound project was set up by Rothoblaas to give more insight into the vibration reduction index  $K_{ij}$ . For the measurements campaign, seven different CLT manufacturers provided panels of a C24 strength class. Also, different connector types were tested among which screws, plates, hold-downs and angle brackets. Measurements were executed with and without elastic interlayers between the connected CLT elements. Elastic interlayers are applied to reduce the flanking sound transmission and therefore increase the vibration reduction index. The effect of the elastics interlayer is also dependent on the used connectors. The goal was to contribute to the development of acoustic design for CLT buildings [12]. The measurements are according to the ISO 10848-1 standard.

In figure 3.6, 3.7, and 3.8 measured data for a T-junction is compared to values that result from the formulas given in the ISO 12354-1. As can be seen, these values highly differ in the low and high frequencies. For the low frequencies, the  $K_{ij}$  is overestimated. Whilst in the high frequencies, the  $K_{ij}$  is underestimated. Since the low-frequency range is already a point of concern the overestimation of the  $K_{ij}$  in the low frequencies should be kept in mind. An overestimation of the vibration reduction index will result in an overestimation of the sound reduction values.

The T-junctions without a resilient interlayer show a higher variance in the measured data. In the frequency range up to 500 Hz, the average variance is around 7 dB. The T-junctions with an interlayer show an average variance of 4 dB in the frequency range up to 500 Hz. Below 400 Hz the junctions without an interlayer have an equal or slightly higher vibration reduction index compared to junctions with an interlayer.

The results show that the index is dependent on the connector type. Whilst different boundary conditions show little differences. This indicates that the CLT elements are damped regardless of the boundary conditions [24]. The measured values differ from the values obtained with the formulas in the EN 12354-1. Especially in the low and high-frequency range, the differences become larger. The high internal loss factor of CLT should allow for normalized formulas based on the geometry only [24].

The critical frequency of cross-laminated elements is in the frequency range of interest. Therefore to estimate the vibration reduction index correctly the contribution of resonant transmission must be taken into account [24].



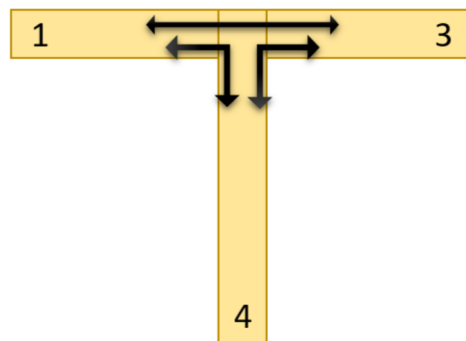


Figure 3.5: Number of the panels for the vibration reduction index

### 3.2.1. ELASTIC INTERLAYER

Junctions with elastic interlayers show higher damping at frequencies above 100 Hz. But in order to create a stiff junction metal fasteners are needed. These metal fasteners in combination with an elastic interlayer show higher damping at frequencies above 250 Hz [61]. This is above the most critical frequency for reducing the sound transmission in CLT buildings.

The measurement results in figure 3.6, 3.7 and 3.8 show even higher frequencies before the effect of the elastic interlayer becomes noticeable. Below 800 Hz the effect of the elastic interlayer is insignificant.

The building code does not give a method to determine the effect of an elastic interlayer between CLT junctions.

### 3.2.2. CONNECTION METHOD

With concrete buildings the junctions are continuous. CLT elements are joined together with metallic connectors, which makes the connection different from the traditional building industry. The measurement results in figure 3.6, 3.7 and 3.8 show that the type and number of connectors have an influence on the vibration reduction index. The figures show 5 different types of connectors and the variances are significant for all three paths. The building code does not give a method to determine the effect of connectors between CLT junctions.

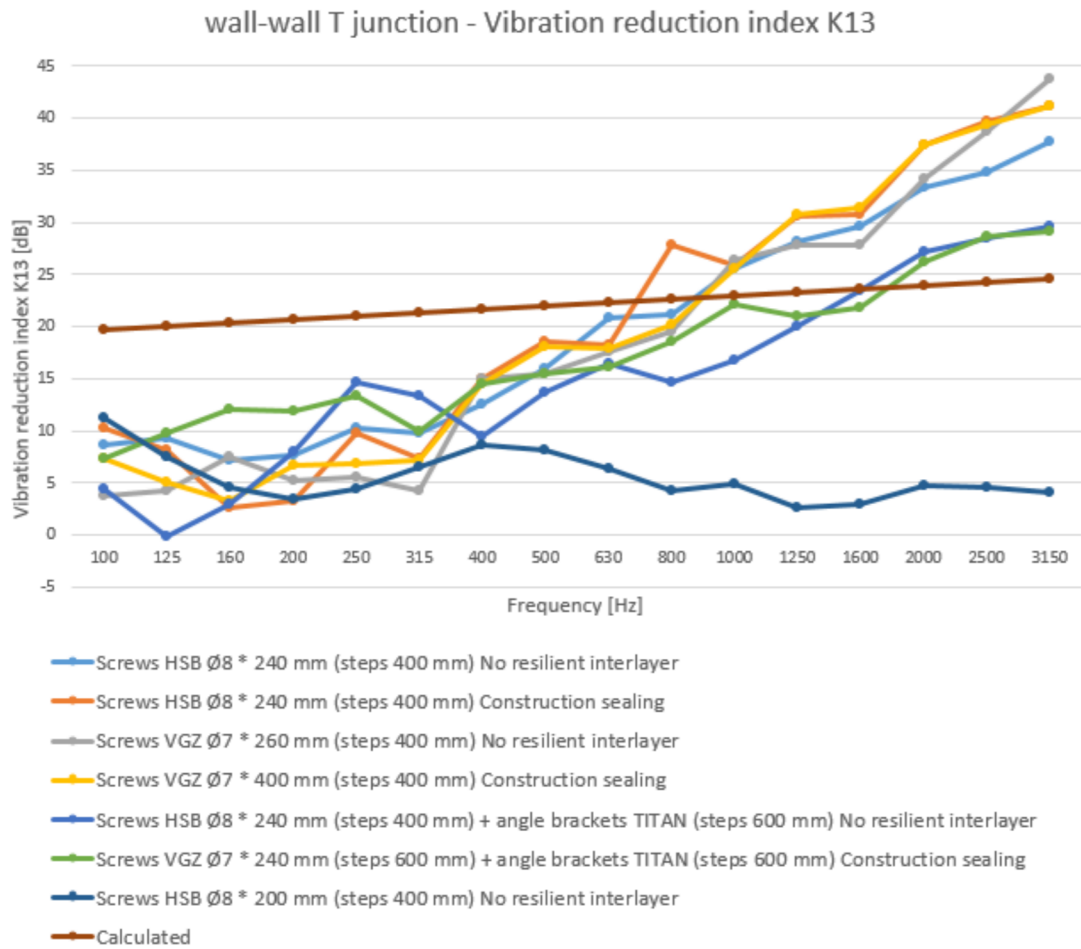


Figure 3.6: T-junction measured data K13 compared to ISO 12354-1 [12]

wall-wall T-junction - Vibration reduction index K14

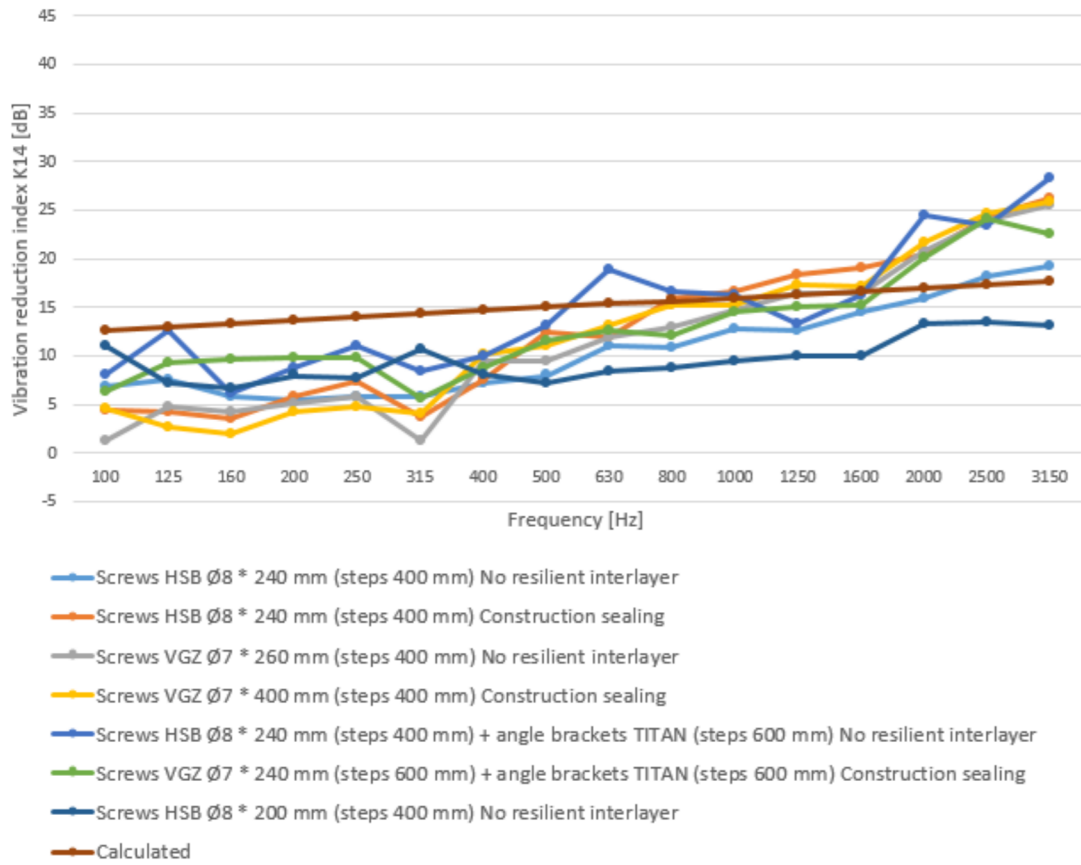


Figure 3.7: T-junction measured data K14 compared to ISO 12354-1 [12]

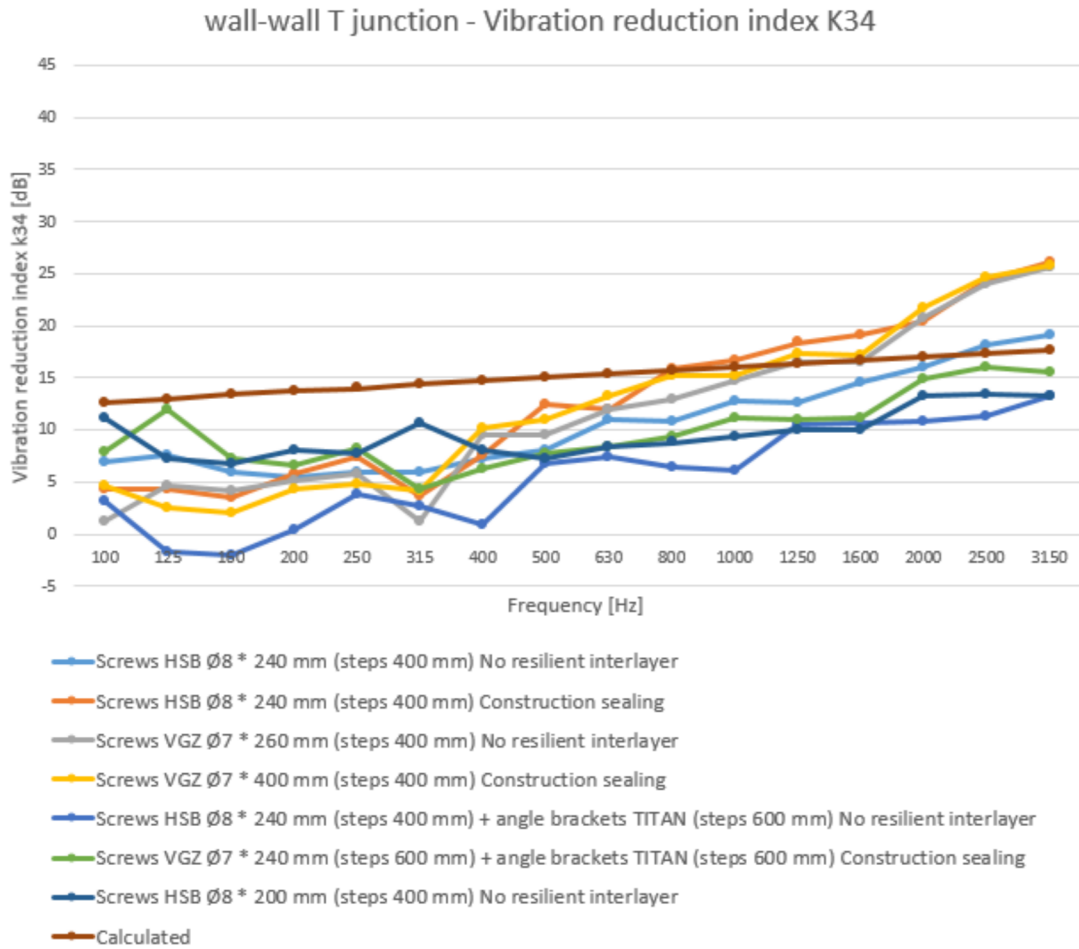


Figure 3.8: T-junction measured data K34 compared to ISO 12354-1 [12]

### 3.3. ADDITIONAL LINING

A way to increase the sound reduction of an element is to apply additional linings. For example, gypsum boards, concrete layers, floating floors, or sound absorption panels. To get a value for additional sound reduction ( $\Delta R_i$ ) for a specific type of lining two measurements are required. One measurement of the bare element and one with the additional lining on one side of the bare element. It is also possible to test with lining on two sides. The additional sound reduction can be calculated with the following equation:

$$\Delta R_i = R_{\text{additional lining},i} - R_{\text{bare},i} \quad (3.1)$$

There are two ways to estimate the additional sound reduction for elements with additional lining on both sides. It is possible to test the bare element and the same element with the lining on both sides. The other option is to test the bare element, the bare element with lining on one side and the bare element with lining on the other side. This is a less exact approach but in this way, more combinations of different types of linings can be estimated. The effect of lining on both sides is not just the addition of the two. As one lining can outweigh the effect of the other.

A large number of additional linings is already tested on concrete elements. But when applying the same lining on a concrete and a CLT element the additional sound reduction will be different. The research was done to make this large database available for CLT constructions. The aim was to create a reference curve that would make it able to convert the data measured on a concrete member to data applicable for CLT elements.

The preference is to use data obtained in the same lab. In this case, the largest possible number of parameters is constant. This will result in the best data for the additional sound reduction. Two cases were chosen to investigate in this research, the build-ups are shown in figure 3.9. The sound reduction of the two different build-ups is presented in figure 3.10. The sound reduction of the bare elements is also included in the graph.

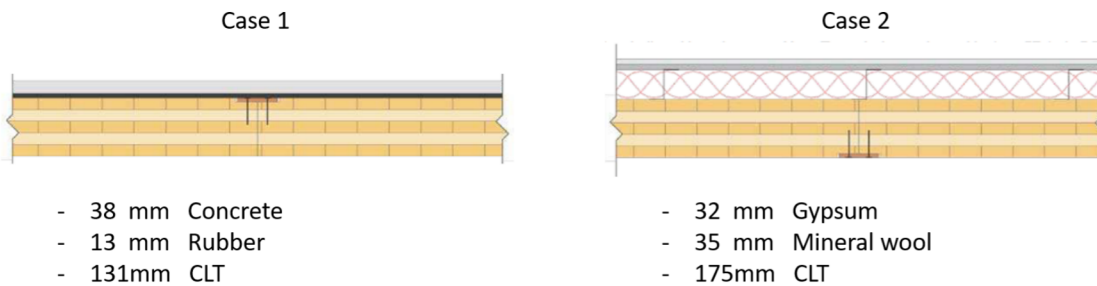


Figure 3.9: The build-ups of two different cases of additional lining

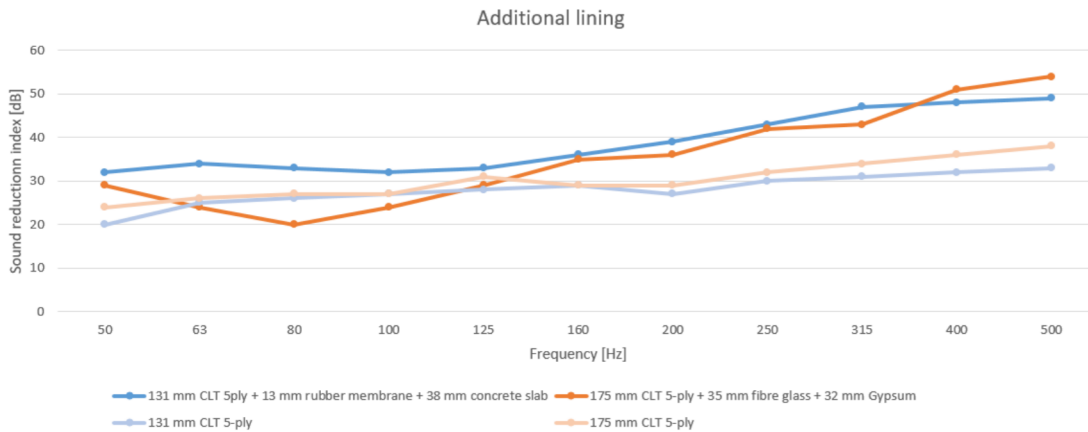


Figure 3.10: The measured sound reduction of a 131 mm CLT 5-ply element + 13 rubber + 38 mm concrete and a 175 mm CLT 5-ply element + 35 mm fibre glass + 32 mm gypsum and the bare CLT element for comparison [19]

The additional lining does not always improve the sound reduction for each frequency. It is possible to get a negative value. This negative sound reduction is due to the mass-air-mass resonance. Also at the critical frequency of the additional lining, there will be a dip in the additional sound insulation [18]. If on both sides of the CLT element the same lining is used the positive sound reduction will become more positive but the negative dips will also become more negative. This shows that additional linings should be designed with care in order to improve the total sound reduction. This dip in the sound insulation can be seen in figure 3.10. For the element with fibreglass and gypsum, the sound reduction decreases around 80 Hz. This is the mass-air-mass resonance frequency.

Different measures are possible to improve the total additional sound reduction: increase the mass of the CLT element, increase the mass of the additional lining, increase the air gap between the CLT element and the lining or fill the air gap with sound-absorbing material [18].

National Research Council of Canada performed measurements on three different base elements, including CLT elements, with the same additional linings [62]. The three different base elements were tested with the same elastic layer of 9 mm (close cell foam mat) and a concrete topping of 38 mm on top of the base. The three base elements were: 200 mm concrete, 175 mm CLT (5-ply), and 245 mm CLT (7-ply). The results show that the additional direct impact sound insulation is higher for the lightweight CLT base elements. In the higher frequencies, the effect is significantly higher on the concrete base element. This also shows that the additional sound reduction by additional lining tested on a concrete base material is not representative of the additional sound reduction on a CLT element.

### 3.4. CONCLUSION

It was investigated which measures affect the total sound transmission between rooms. There are several measures to reduce the amount of sound transmission. A distinction is made for measures to reduce the direct sound and the flanking sound. In order to reduce the direct sound transmission, additional linings can be placed on the room separating elements. This will also affect the total amount of flanking transmission, as the amount of energy transmitted to flanking elements will be limited by the additional linings. Important is that the linings are placed correctly to avoid additional flanking paths and the dip in the sound insulation at the mass-air-mass resonance frequency. To reduce the vibration reduction indices the type and number of connectors can be of importance, as the measurement results showed a high variance. Another measure that affects the vibration reduction index is the presence of an elastic interlayer. The effect of the elastic interlayer is limited in the low-frequency range.

The measured effects of these different sound reduction measures are given in this chapter. What can be concluded are the following points:

- The thickness of the CLT elements influences the direct sound transmission, as more mass results in more sound reduction. A thicker panel results in a higher sound reduction.
- The variance between measurements of panels with the same thickness can be significant. The changes can be up to 9 dB. The variances are largest around the panels' first resonance frequency. The variance between the weighted values are smaller and only differ 1 a 2 dB.
- The type and number of connectors can have a significant influence on the vibration reduction index. The differences between measurements of the same junction with a different number or type of connectors can be up to 10 dB per frequency in the low-frequency range.
- The effect of an elastic interlayer is limited in the low-frequency range. The differences are within a range of 3 dB. The influence of the interlayer can also be negative on the sound reduction.

# 4

## NUMERICAL SOUND TRANSMISSION MODEL

There are several ways to estimate the flanking sound transmission through junctions. The standard code to estimate the sound transmission between rooms is the EN 12354. This code gives a method that is mainly based upon empirical equations of heavyweight constructions. According to literature FEM (finite element method) and SEA (statistical energy analysis) can also be used to estimate the sound transmission [63]. FEM can be used to estimate the transmission of the low frequencies and SEA can be used for the mid and high-frequency range. As low-frequency sounds are a concern in lightweight problems FEM models will be used to estimate the direct sound transmission and the vibration reduction index. The difference between the vibration reduction index measured and obtained with FEM is generally within the range of 5 dB difference from the measured data for lightweight constructions [63].

The question is: *'How can a numerical sound transmission model be developed?'* In this chapter, the details of the numerical model and calculation procedure will be explained. The simulation process contains three steps: pre-processing, solution processing, and post-processing. The first two steps are performed in Ansys and the last step in Excel. By going over all the design parameters, the most influential parameters can be identified.

### **Pre-processing:**

- Geometry development
- Material properties
- Mesh generation
- Boundary conditions

### **Solution processing:**

- External loads
- Analysis type
- Solve system of equations

### **Post-processing:**

- Process results
- Visualize results
- Evaluate results



## 4.1. GENERAL MODELLING IN ANSYS

### 4.1.1. ANALYSIS TYPES

Three different analysis types are used to obtain the direct sound transmission and vibration reduction index in Ansys. The modal and harmonic analyses are used for the vibration reduction index. The harmonic acoustic analysis is used for the direct and total sound transmission.

#### MODAL ANALYSIS

Modal analysis determines the natural frequencies and mode shapes of a structure. This analysis is usually the starting point for more detailed analysis like the harmonic analysis. The assumption is that the structure has a constant mass and stiffness and that there are no external forces [64].

The general equation of motion in matrix notation for the modal analysis of an undamped system:

$$[M]\{\ddot{u}\} + [K]\{u\} = \{0\} \quad (4.1)$$

Respectively [M], [C], and [K] are the mass, damping, and stiffness matrices. Vector  $u$  is the displacement factor.

#### HARMONIC ANALYSIS

A harmonic analysis determines the steady-state response of a structure subjected to a sinusoidal load which varies over time. This analysis can determine the vibration reduction indices of the junctions. The harmonic analysis is linear, so it ignores non-linearity like plasticity. The assumptions are that the structure has a frequency-dependent mass, damping, stiffness, and the external loads must be a real value [64].

The general equation of motion in matrix notation for the harmonic analysis is:

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{f\} \quad (4.2)$$

$f$  is the external load vector.

#### HARMONIC ACOUSTIC ANALYSIS

Acoustic analysis and simulations can determine the propagation of acoustic waves in an acoustic medium. The assumption is that the change of pressure created by a sound wave is relatively small compared to the average sound pressure in the acoustic medium. The sound source creates sound waves, which travel through the fluid until they encounter the structure. Introducing a fluid-structure interaction makes it possible to determine the interaction of the acoustic wave and the solid structural elements. In this way, it is possible to estimate the sound transmission level through the elements.

Harmonic acoustic analysis determines the steady-state response of a structure and the acoustic medium under excitations that varies harmonically over time. In a coupled acoustic-structural analysis the following equations are solved: the structural dynamics equation, the linearized Navier-Stokes equations of fluid momentum, and the flow continuity equation. To get the acoustic wave equation from the Navier-Stokes and flow continuity equations four assumptions need to be made:

- The fluid is compressible
- The fluid is inviscid
- The flow rate of the fluid is constant
- The fluid has a uniform mean density and pressure [64]

These equations combined with the assumptions create the following dynamic matrix equation that the program solves for each frequency of interest [64]:

$$-\omega^2 \begin{bmatrix} [M_S] & 0 \\ \rho_0 [R]^T & [M_F] \end{bmatrix} \begin{Bmatrix} \dot{u}_e \\ \dot{p}_e \end{Bmatrix} + j\omega \begin{bmatrix} [C_S] & 0 \\ 0 & [C_F] \end{bmatrix} \begin{Bmatrix} \dot{u}_e \\ \dot{p}_e \end{Bmatrix} + \begin{bmatrix} [K_S] & -[R] \\ 0 & [K_F] \end{bmatrix} \begin{Bmatrix} u_e \\ p_e \end{Bmatrix} = \begin{Bmatrix} f_S \\ f_F \end{Bmatrix} \quad (4.3)$$

$\omega$  is the analyzed frequency,  $j$  is an imaginary unit,  $u$  and  $p$  are the displacement vector and the acoustic fluid pressure vector, and  $f$  is the external load vector. [R] is the coupling matrix that represents the coupling conditions between the acoustic medium and the structure [64].

The frequency range of interest needs to be defined by the first and last frequency of interest and the number of steps required. The frequency steps are logarithmic. The first frequency of interest is 50 Hz and the last is 500 Hz. The program calculates the lower, centre, and upper band limits of the 1/3 octave bands. The lower, centre and upper band frequencies used are given in the table below. Averaging the results of each 1/3 octave band mitigates the effect of local variations and allows a more general trend to be observed than by analysing each frequency.

Lower band [Hz]	Centre band [Hz]	Upper band [Hz]
44,7	50	56,2
56,2	63	70,8
70,8	80	89,1
89,1	100	112
112	125	141
141	160	178
178	200	224
224	250	282
282	315	355
355	400	447
447	500	562

Table 4.1: The lower, centre and upper band frequencies used to determine the sound transmission in the 1/3 octave bands

#### 4.1.2. DAMPING

The damping matrix  $[C]$  in its most general form for harmonic acoustic analysis is the following:

$$[C] = \alpha[M] + \beta[K] + \sum \beta_j [K]_j + \beta_c [K] + [C]_\xi + \sum [C]_k \quad (4.4)$$

$\alpha$  and  $\beta$  are the Rayleigh damping constants for the mass and stiffness matrix ( $[M]$  and  $[K]$ ).  $\beta_j$  is the material-dependent boundary admittance, also called the absorption factor. This absorption factor is a constant damping factor.  $\beta_c$  is the frequency-dependent stiffness matrix multiplier.  $[C]_\xi$  is the frequency-dependent damping matrix and  $[C]_k$  is the element damping matrix [64].

Research shows that to obtain realistic results in the low-frequency range it is necessary frequency-dependent boundary admittance and structural damping. Using a constant damping parameter ( $\xi$ ) is effective for low frequencies. For higher frequencies the results become unrealistic. Using frequency-dependent Rayleigh damping shows more realistic results in the higher frequencies [20]. As the constant damping parameter show realistic results in the low-frequency range, this is the type of damping included in the model.

Since the internal damping ( $\eta$ ) of CLT is above 3% it is assumed that the internal damping is the only significant amount of damping in the structure. Therefore the internal loss factor will be used in stead of the constant damping parameter ( $\xi$ ).

### 4.1.3. FLUID-STRUCTURE INTERACTION

In the simulation, there is a real-time coupling between the solid and fluid elements. This coupling is called the fluid-structure interaction (FSI). In this way, the structure can be set into vibration by the acoustic waves in the fluid and vice versa. The interface element between the fluid and the structure is illustrated in figure 4.1. When using the FSI the structural damping can be defined in the material properties. The acoustic boundary admittance can now be modelled with an absorption face on the acoustic medium.

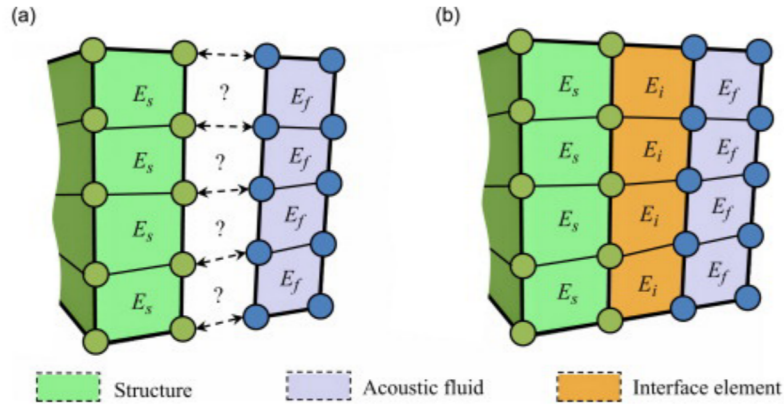


Figure 4.1: (a) fluid and solid elements; (b) Fluid-structure interaction between the fluid and solid elements [20]

### 4.1.4. ELEMENTS

The finite elements models contain different types of elements. Here the three used types are mentioned and shortly explained.

#### FLUID ELEMENTS

Modelling the elements in the fluid domain is done with FLUID220 elements. FLUID220 are the higher-order 3D 20-node solid element that shows quadratic pressure behaviour. The elements include damping within the fluid. The absorption coefficients can be defined on the faces of the elements [21]. The air volumes inside the send and receiver room are modelled with fluid elements.

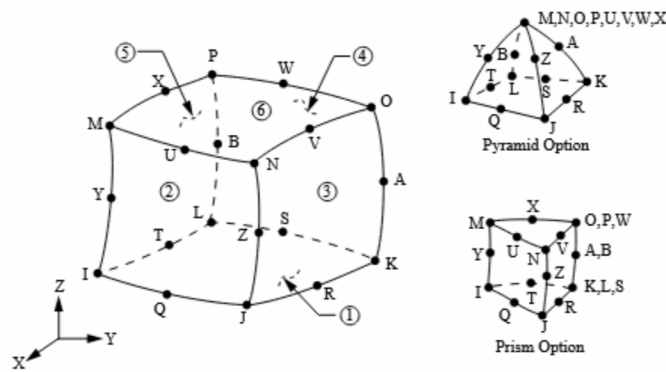


Figure 4.2: FLUID220 3-D acoustic fluid 20-node solid element [21]

### SOLID ELEMENTS

The structural elements are modelled with SOLID186 elements. This element is a higher-order 3D 20-node solid element that shows quadratic displacement behaviour [21]. The solid elements can include internal damping. The elements are used for all solid elements in the models.

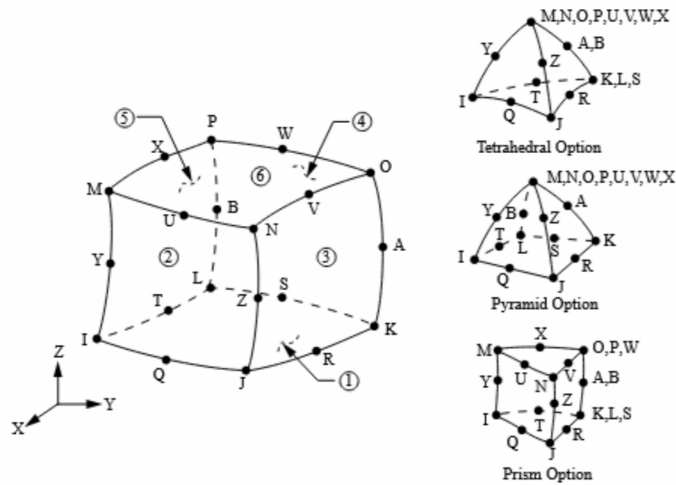


Figure 4.3: SOLID186 3-D 20-node structural solid [21]

#### 4.1.5. CONTACT REGIONS

The contact, friction, and sliding between elements are modelled with CONTA174 elements. These elements are located on the surfaces of the 3D solid or fluid elements. Contact occurs when an element penetrates the target surface. The target surface elements are modelled as TARGE170 elements. These elements together create bonded or frictional contact between the solid or fluid elements [21].

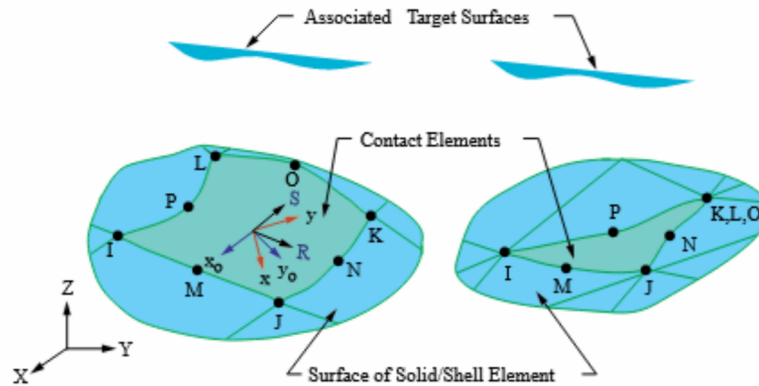


Figure 4.4: CONTA174 3-D 8-node surface-to-surface contact [21]

Contact regions are either bonded or frictional. Bonded contact means that sliding and separation is not possible between the contact regions. The program solves the model and closes any gaps that might occur between bonded contact regions. The CLT lamellas are glued together so, no sliding or separation is possible. Therefore the contact between the lamellas is modelled as bonded.

Contact regions can also be modelled with a friction coefficient. ANSYS makes use of Coulomb friction. Above the friction coefficient, the contact regions are bonded. When the shear stress reaches the friction coefficient the contact regions start to slide. Gaps between contact regions are not closed by the program. The connection between different CLT elements is not glued, these connections have a friction coefficient. The friction coefficient between timber elements is assumed to be around 0.4.

#### 4.1.6. MESH SIZE

The mesh size needs to be defined appropriately to obtain realistic results. For a realistic simulation of the sound wave, there should be at least 6 to 10 elements per wavelength [65], as illustrated in figure 4.5. Therefore the minimal mesh size is the speed of sounds divided by eight times the highest frequency of interest. The SOLID186 elements have an additional node halfway. Therefore the size of the mesh can be doubled. So, the minimum mesh size is now divided by four. The wavelength of the highest frequency of interest will be governing.

$$\text{Meshsize} = \frac{c}{4 * f} \quad (4.5)$$

The highest frequency of interest is 562 Hz. Therefore the mesh size should minimally be 0.15 m. A finer mesh will result in more precise results but as said this will also increase the computation time. It should be noted that the higher the frequency, the shorter the wavelength. For a smaller wavelength, the details in the geometry become more significant. Modelling more details and using a finer mesh result in longer computational times for the FE models.

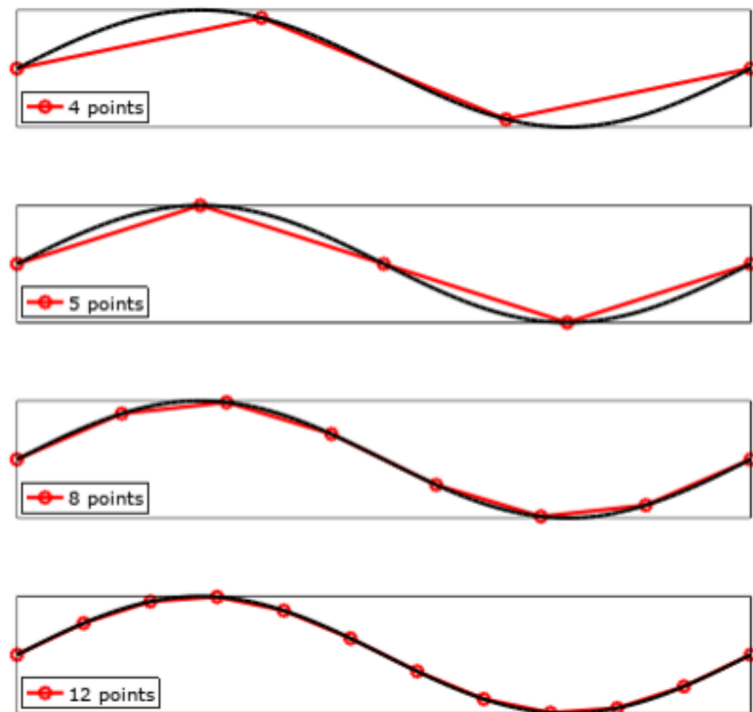


Figure 4.5: Elements per sound wave [22]

## 4.2. NUMERICAL DIRECT SOUND TRANSMISSION MODEL

This section is dedicated to the modelling of the direct sound transmission in Ansys. The experiments set up is mimicked in Ansys. In this way, the results can be compared to the empirical data to validate the model.

### 4.2.1. EXPERIMENT SET-UP

The measurement data used to validate the models is experimental data. The NRC performed the experiments in their Construction Wall Sound Transmission Facility. They performed the measurements according to the ASTM E90 standards. The facility consists of two reverberation rooms, one large room of 255 m<sup>3</sup> and a smaller room of 140 m<sup>3</sup>. All the walls are rigid walls with very low absorption coefficients. Calibrated microphones of Bruel & Kjaer (type 4166 or type 4165) are present in both rooms. During a measurement, the microphone is moved to 9 different locations. The sound source is a bi-amped loudspeaker driven by separate amplifiers and noise sources. Rigid panels under different angles are present in both rooms to create a diffuse sound field [19]. An illustration of a send and receiver room with a test element in-between is shown in figure 4.6.

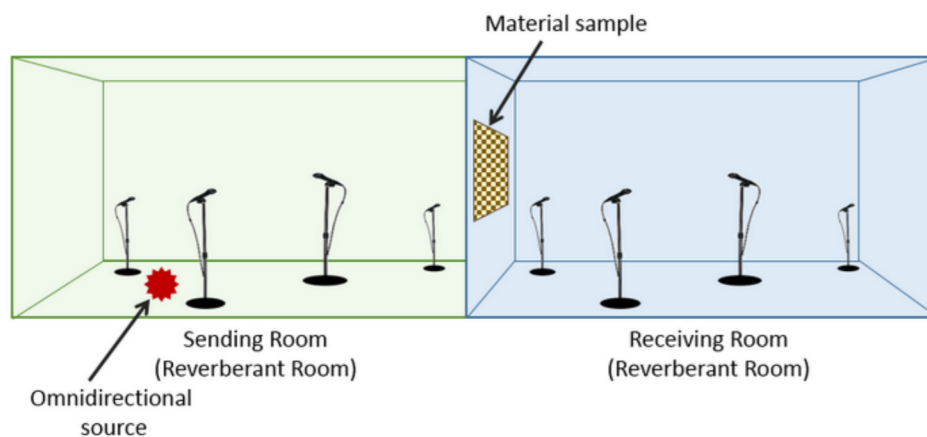


Figure 4.6: Measurement set up for the direct sound transmission [23]

The dimensions of the tested elements were 3,66 \* 2,44 m. The test element fits in the opening between the send and the receiver room and is resting but not attached to the test frame. Gaps between the test frame and the test element are filled with glass fibres, which is highly sound-absorbing material. In this way, it is guaranteed that there are no sound leaks. All the flanking paths are blocked, so the sound transmitted is only direct sound [19]. The CLT panels have adhesive between the faces of the lamellas in the adjacent layers, but not between the adjacent elements within a given layer. There were noticeable gaps up to 3 mm between some of the elements in a layer[14].

For both the send and receiver room they measured the average sound pressure level in one-third octave bands in the frequency range 50 - 5000 Hz. The sound transmission loss is the difference between the sound pressure levels in the send and receiver room and corrected with a term for the amount of absorption in the receiver room and the area of the test element [19].

### 4.2.2. GEOMETRY

The geometry for the direct sound transmission model is simple. The model consists of 3 elements. The air volume of the sending room. The send room is 3 m wide, 4 m long, and 3 m high. The CLT panel is 3\*3 m. The last element is the air volume of the receiver room (3\*3\*4 m). The geometry of a 5-ply CLT element is shown in figure 4.7.

The geometry of models with additional linings is in the base the same as the geometry of a bare CLT element. Additional solid layers are placed in between the CLT element and the air volumes. The elements have the same size as the CLT element (3\*3 m). The thickness of the layers is the thickness of the layer used in the building. In this way, different build-ups can be created.



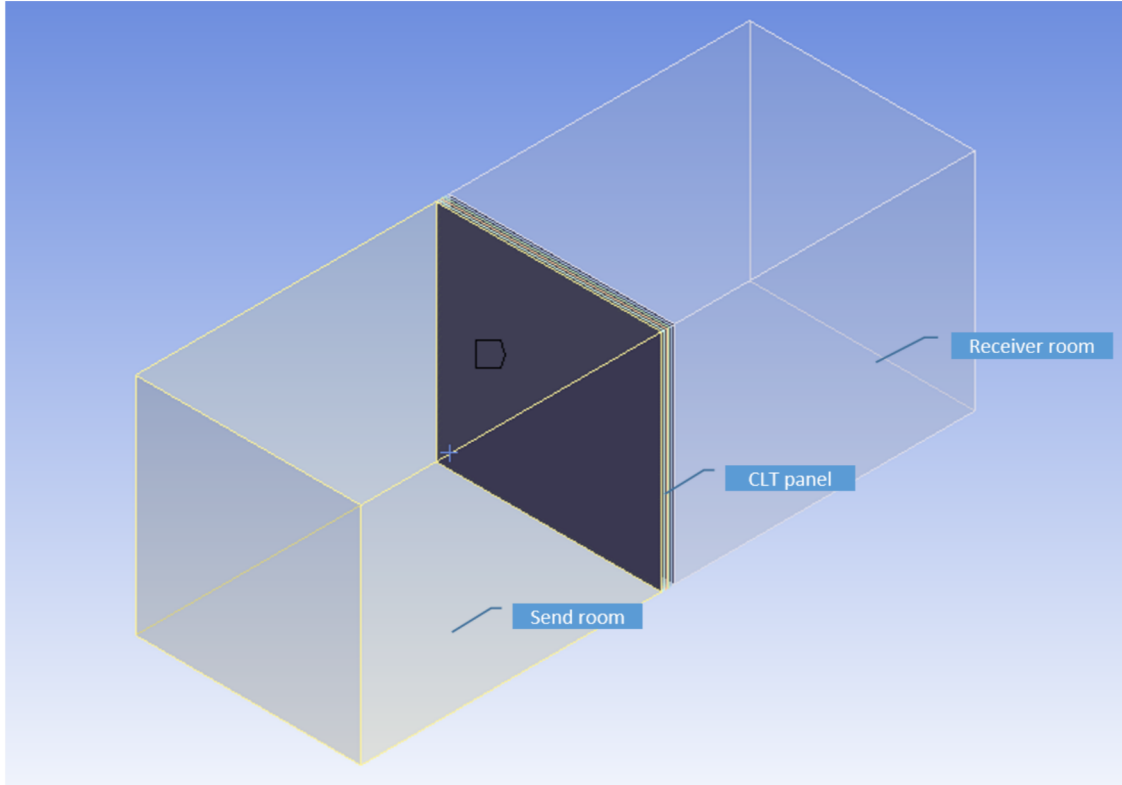


Figure 4.7: Elements in the FEM: the air volume in the send room, the 5 CLT layers (CLT panel) and the air volume of the receiver room

### 4.2.3. MATERIAL PROPERTIES

The solid elements need a density, Young's modulus, Poisson's ratio, shear modulus, and a material damping coefficient. The material properties in table 4.3 are the material properties used in the model. These material properties are based on material properties found in the literature. The material properties in literature show a large variance [38][66].

Two separate acoustic fluid elements represent the air volumes of the rooms. The acoustic fluid elements need a density and the speed of sound in the fluid. Other structural elements need a density, Young's modulus, Poisson's ratio, and material internal damping coefficient. The material properties used in the models are given in table 4.2.

Material	Air	Gypsum	Steel	Concrete	Mineral wool	Rubber	Bamboo
$\rho$ [ $kg/m^3$ ]	1,125	1000	7850	2300	17	348	1150
E [MPa]	-	2500	200000	30000	0,1	0,4	13565
$\nu$ [-]	-	0,25	0,3	0,18	0	0,2	0,1
$\eta$ [-]	-	0,01	0,025	0,01	0,3	0,4	0,01
c [ $m/s$ ]	343	-	-	-	-	-	-

Table 4.2: Material properties used for air, gypsum, steel, concrete, mineral wool, rubber and bamboo in the FEM [32] [33] [34] [35]



Type of modeling	Layered CLT elements
$\rho$ [ $kg/m^3$ ]	500
$E_x$ [MPa]	11000
$E_y$ [MPa]	300
$E_z$ [MPa]	300
$G_{xy}$ [Mpa]	650
$G_{yz}$ [Mpa]	65
$G_{xz}$ [Mpa]	650
$\nu_{xy}$ [-]	0,3
$\nu_{yz}$ [-]	0,4
$\nu_{xz}$ [-]	0,3
$\eta$	0,08

Table 4.3: Material properties used for the CLT in the FEM

#### 4.2.4. BOUNDARY CONDITIONS

The boundary conditions need to be defined adequately. The boundary conditions can have a significant influence on the stiffness and natural frequencies of the elements [67]. In the test situation, the test report states that the test element was resting on and not attached to the test frame. The air gaps between the element and the test frame were filled with glass fibres [19]. Since the air gaps between the element and the test frame are filled with glass fibres it is assumed that there are no leaks.

Fluid solid interfaces are generated in between the air and the test element. The interfaces are applied on both the send and receiver sides of the element. At these same interfaces, the absorption surfaces are created. The amount of absorption depends on the type of material. The absorption coefficients per type of material are stated in Appendix C.

The faces of the air volume which are not in contact with the structural element are rigid boundaries. The rigid boundaries do not absorb any sound but reflect it all back into the room.

#### 4.2.5. MESH

The highest frequency of interest is 562 Hz. This means the minimal required mesh size is 0,15 m. Figure 4.8 shows the mesh of the model.

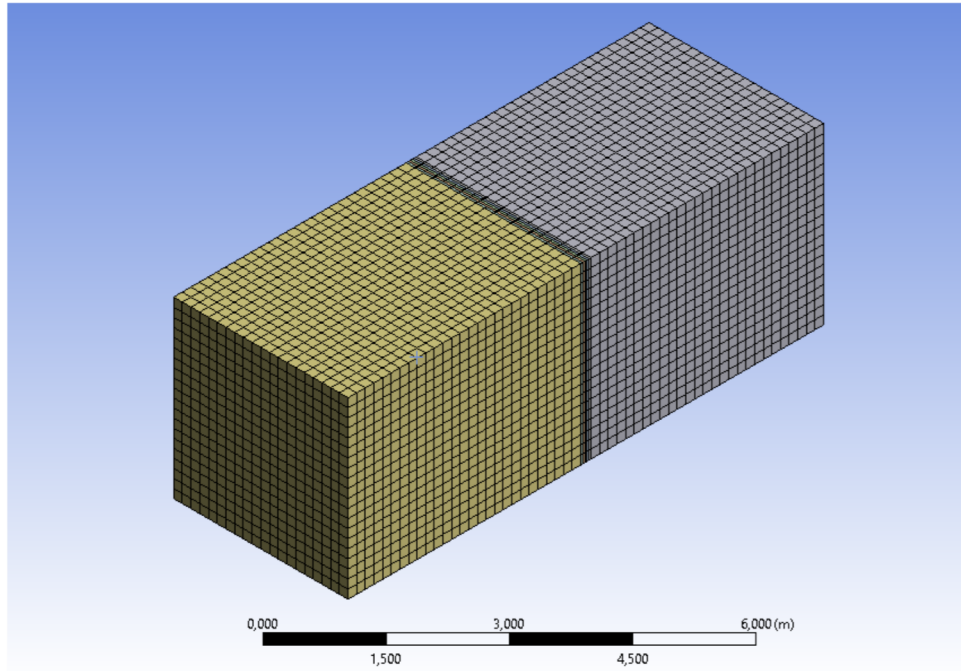


Figure 4.8: Mesh in the FEM - minimal mesh size = 0,15m

#### 4.2.6. SOUNDS SOURCE

In the sending room, there is a mass sound source that sends pressure waves. This creates a diffuse sound field in the sending room. In this way, the room separating element and the flanking elements are radiated by the sound waves. The position of the sound source is on the backside of the sending room. In this way, the sound distribution is diffuse in the whole sending room. This mass sound source creates a sound by setting the face into vibration with a magnitude of  $1 \text{ kg/m}^2\text{s}$ , as indicated in figure 4.9. This vibration varies harmonically over time.

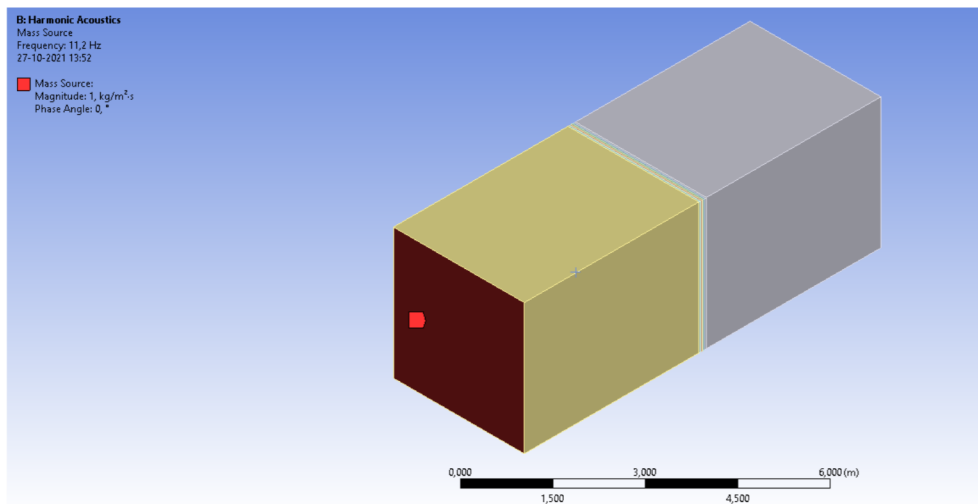


Figure 4.9: Sound source in the FEM at then back side of the send room

### 4.3. NUMERICAL VIBRATION REDUCTION INDEX MODEL

To obtain the sound transmission of each flanking path the vibration reduction of each path needs to be measured. Rothoblaas measured the vibration reduction indices for several configurations. The measurement set-up of Rothoblaas was mimicked in Ansys. The FE analysis determines the velocity levels of the faces of the different panels. Based upon these velocity levels the vibration reduction index can be calculated by using the following formulas [68]:

$$K_{ij} = D_{v,ij} + 10 * \text{LOG}\left(\frac{l_{ij}}{\sqrt{a_i a_j}}\right) \quad (4.6)$$

with:

$$D_{v,ij} = L_{v,i} - L_{v,j} \quad (4.7)$$

$$L_v = 10 * \text{LOG}\left(\frac{v_1^2 + v_2^2 + \dots + v_n^2}{n * v_0^2}\right) \quad (4.8)$$

$v_0$  = reference velocity ( $1 \times 10^{-9}$ ) [m/s]

$v_1, v_2, v_n$  are velocity levels at n different positions on the element [m/s].

The model of the T-junction is validated with the measurement data obtained by Rothoblaas. A comparison is made between the measurement results and the results of the FE analysis.

#### 4.3.1. EXPERIMENT SET-UP

The execution of the experiments was in the test facility of Rothoblaas. The tests are in collaboration with the University of Bologna for the flanksound project. During the experiments, the standard ISO 10848 was followed in the strictest way possible [68]. Seven different manufacturers were responsible for the production of the CLT panels. All the manufacturers have a slightly different production process [24].

The panels are placed on small concrete blocks to minimize ground contact. To guarantee safe working conditions all panels are connected to the concrete blocks with hold downs, as can be seen in figure 4.10. The assumption was that this set-up created a measurement situation not influenced by the boundary conditions. The ISO 10848 recommends free hanging panels. This set-up was thought to be an acceptable alternative [25].



Figure 4.10: Vibration reduction index measurement set-up, the panels are resting on small concrete blocks to which they are connected with hold downs [24]

The choice for the locations of the excitation and measurement points was according to the ISO 10848 standard. The standards give a few guidelines for the locations of the measurement and excitation points. Each element requires a minimum of three different excitation points, each excitation point needs a minimum of three measurement points per panel. The researchers used three excitation points and four measurement points per panel for these measurements [25]. The average of the measurements is taken to reduce the effect of local variations in the material. The following minimum distances are taken into account for the locations of the excitation and measurement points [68]:

- 0,5 m between the excitation point and the element boundary
- 1,0 m between the excitation point and the junction
- 1,0 m between the excitation point and the measurement points
- 0,25 m between the measurement points and the element boundary
- 0,5 m between the individual measurement points

During the experiments the scheme in figure 4.12 was used for the locations of the measurement and excitation points. These locations are with some tolerances, for example, to avoid a knot in the panel. The shaker creates a sinusoidal peak force of 200 N. The shaker is mounted to the panel and standing on a heavy base, see figure 4.11. The measurement points are eyelets that are fixed to the panel with magnets [24].

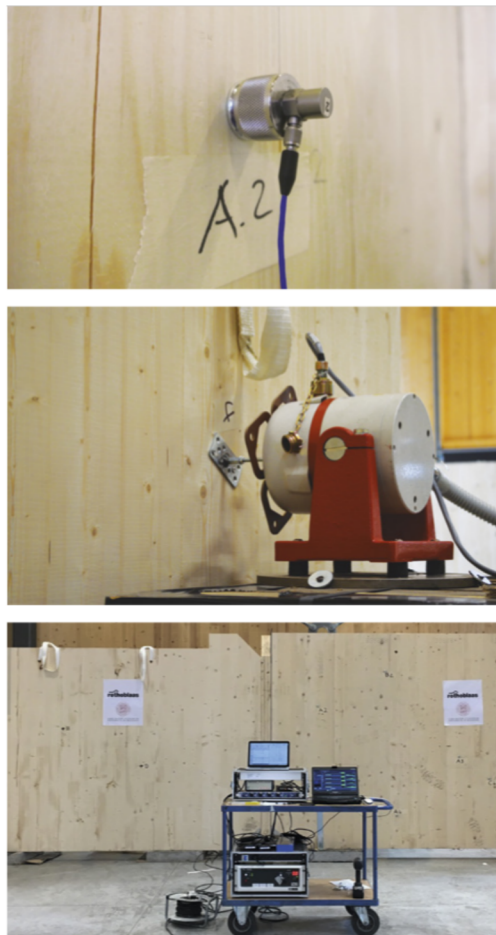


Figure 4.11: The measurement eyelet connected to the panel with magnets; The shaker on a heavy base connected to the panel; The measurement equipment[24]

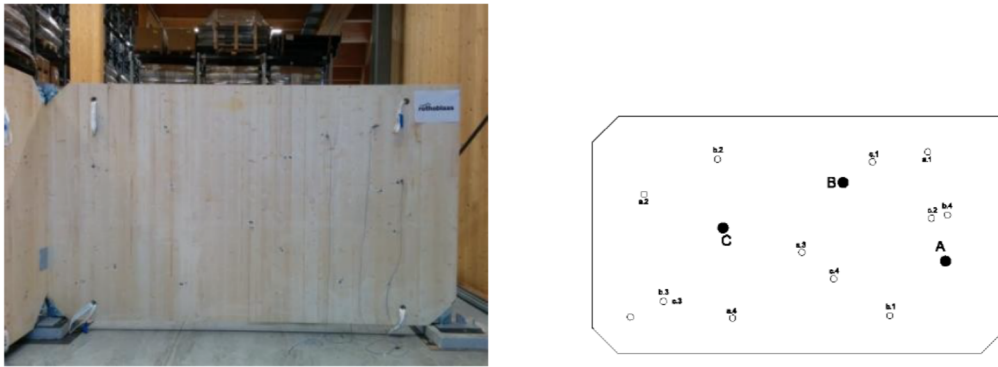


Figure 4.12: CLT panel with the X-RAD connection system fixed to the concrete blocks and the scheme of the measurement and excitation points [25]

#### 4.3.2. GEOMETRY

The geometry for the vibration reduction index consists of three CLT panels. Panel 1 is 4\*3 m, panel 3 is 3,5\*3 m, and panel 4 is 4\*3 m. The 3 CLT layers of the CLT panels have a thickness of 33,3 mm each, which creates the 3-ply CLT elements of 100 mm. The in-plane x- and y-direction of the layers are alternated to create the crosswise CLT panel. The geometry of the T-junction with the numbers of the panels is shown in figure 4.13. In the cases of junctions with an interlayer, there is an element modelled in-between the CLT panels. The interlayer elements have the same height as the CLT panels and are 100 mm wide. The thickness can vary.

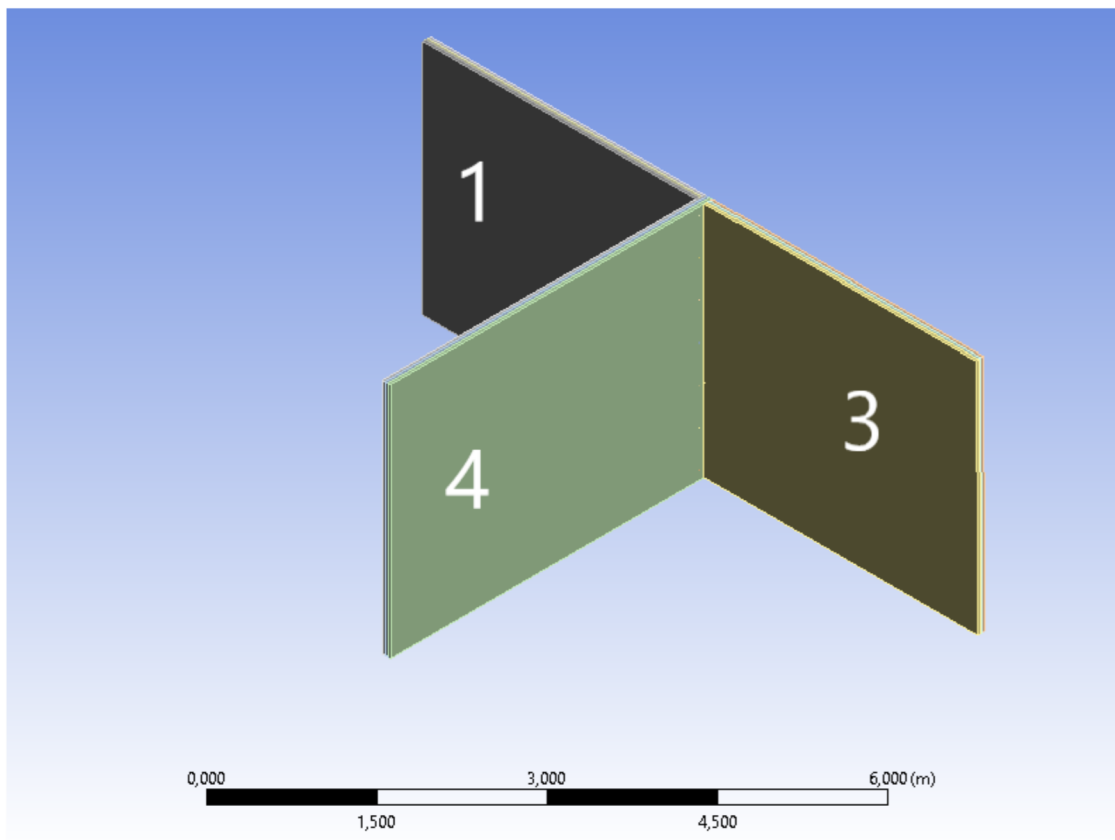


Figure 4.13: Geometry of the panels of the T-junction

### 4.3.3. MATERIAL PROPERTIES

The material properties of the lamellas of the CLT elements are assumed to be the same as the material properties for the CLT lamellas used for the direct sound transmission model. The material properties used in the models are in table 4.3.

The material properties of the interlayers are given in table 4.4. There was made use of three different materials as the interlayer. The first one is construction sealing. Construction sealing is a compressible sealing gasket for regular joints used as a sound isolator, as it provides up to 3 dB of sound reduction. The sealing is produced out of a solid EPDM (ethylene propylene diene monomer) rubber compound and it has a thickness of 3 mm. XYLOFON is a resilient interlayer used to ensure acoustic comfort in timber structures. XYLOFON is a polyurethane compound that is available in 5 different types with elasticity from 35 to 90 shore. The type required for a specific construction is dependent on the amount of load present on the structure. All 5 types have a thickness of 6 mm. The last type of interlayer investigated is cork. Cork is a natural material used for sound insulation.

Material	Sealing	XYLO35	XYLO50	XYLO70	XYLO80	XYLO90	Cork
$\rho$ [ $kg/m^3$ ]	480	450	450	450	450	450	240
E [MPa]	2	2,16	3,53	10,1	19	43	1,23
$\nu$ [-]	0,1	0,2	0,2	0,2	0,2	0,2	0,1
$\xi$ [-]	0,1	0,177	0,132	0,101	0,134	0,230	

Table 4.4: Material properties used for elastic interlayers in the FEM [36][12][37]

### 4.3.4. BOUNDARY CONDITIONS

Rotoblaas assumed that this set-up creates a measurement situation that is not influenced by the boundary conditions. Since the direct sound transmission is significantly influenced by the boundary conditions the impact of the hold-downs is investigated. In the test situation, the panels are connected to concrete blocks by hold-downs. The hold-downs are located near the side edges of the panel. To mimic the connections the outer corners of the CLT panels are given a zero displacement.



#### 4.3.5. MESH

The highest frequency of interest is 630 Hz. This means that the minimum mesh size is 0,15m. Figure 4.14 shows a visualization of the mesh of the T-junction model.

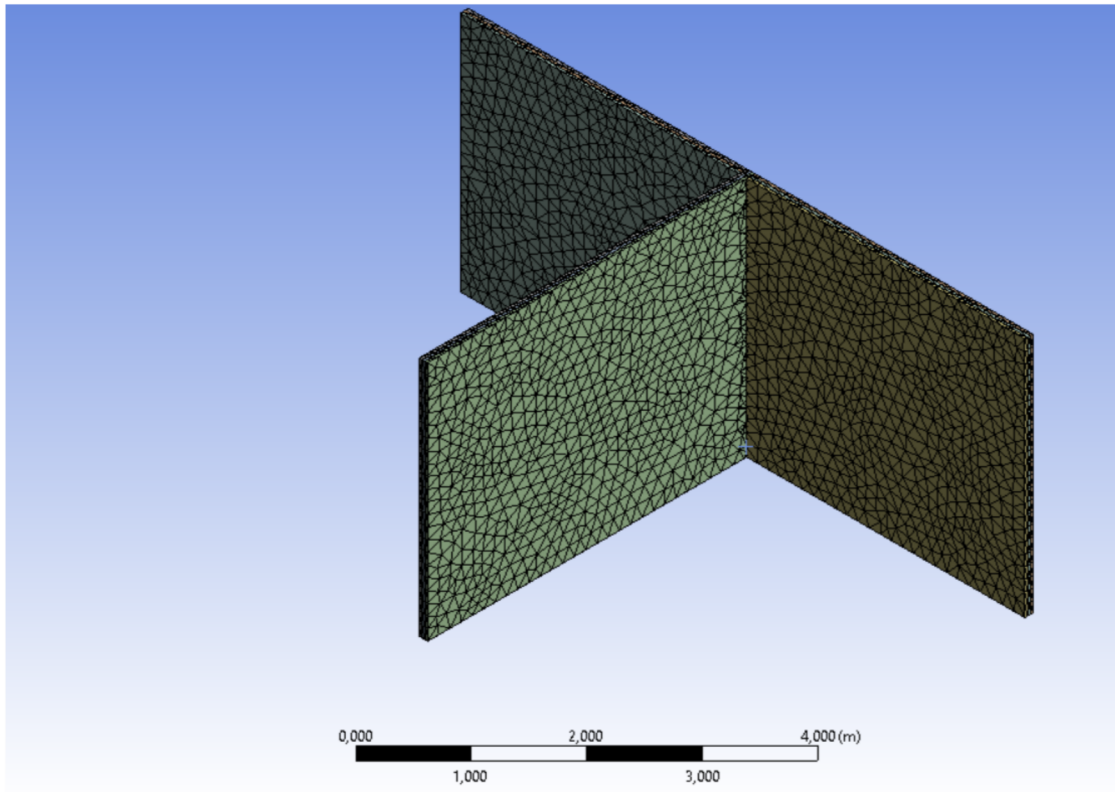


Figure 4.14: T-junction model with a mesh size of 0,14 m

#### 4.3.6. LOAD VECTOR

At the excitation points, a sinusoidal peak force of 200 N is active. This is similar to the load excitation in the measurements. In total, the model is running nine times, as there are three excitation positions on each panel. The position of the load excitation points and the measurement points is based on the scheme used by Rothoblaas, figure 4.12. The locations of the excitation and measurement points in the model are shown in figure 4.15 for panel 1. For panel 3 and 4 the points are on similar locations. The excitation and measurement points are modeled as small face elements of 0,01\*0,01 m. The face elements connected fully bonded to the outer CLT lammela.

#### 4.3.7. CONNECTION BETWEEN THE PANELS

The CLT panels are connected with a number of connectors. Different FEM modelling approaches can be used to model the bolted connections between the CLT panels. They are compared based on the amount of pre-processing, computational time and modelling accuracy in Appendix E. According to the measurements results of Rothoblaas the type, size, and amount of bolts influences the vibration reduction index.

The CLT panels are only connected with the connectors and not glued together in the test situation. Therefore the contact regions between the panels are frictionally bonded. The CLT panels have a friction coefficient of 0,4 (timber to timber friction coefficient) [69].



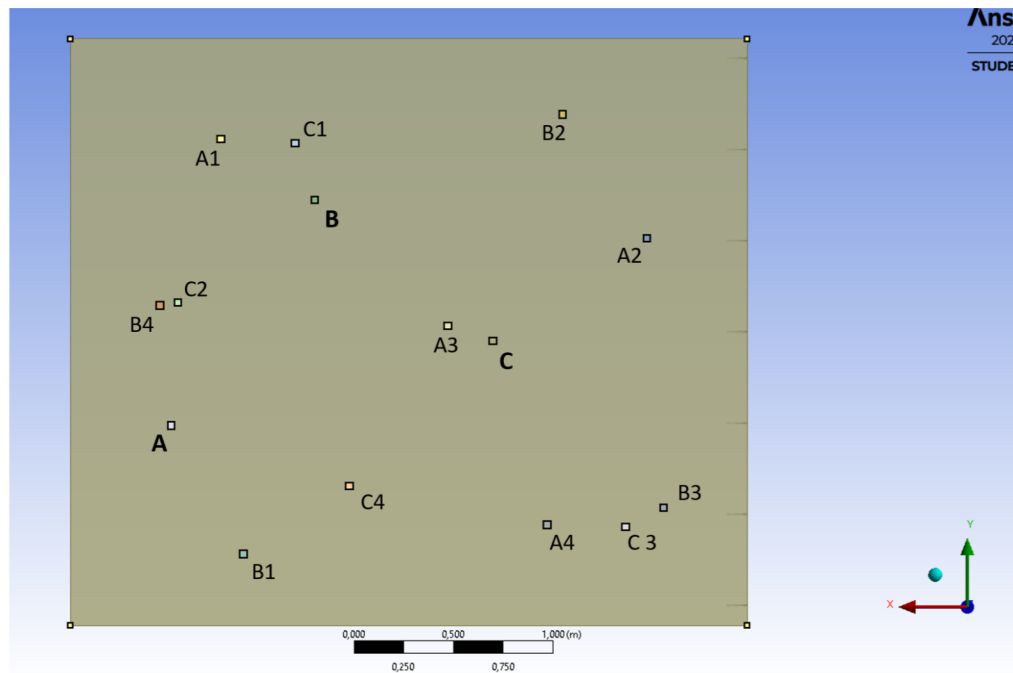


Figure 4.15: The excitation points A, B and C on panel 1 used in the FE model, with the 4 measurement points used for each excitation point

#### 4.4. CONCLUSION

This chapter describes how two different numerical sound transmission models can be developed, namely the direct sound transmission model and the vibration reduction index model. The numerical models mimic the experiment setup of facilities that measured the direct sound transmission and the vibration reduction index. The geometry of the models is in both cases based on the geometry of these experimental set-ups. The contact regions between elements in the models are bonded. The only exception is the contact region between two CLT panels. This contact is modelled as frictionally bonded. In the vibration reduction index model, the effect of the number and type of connectors and the effect of an additional interlayer can be calculated, by modelling the elements in between the panels. The material properties of the different materials in the models are based upon material properties found in literature, as the exact material properties of the CLT elements used in the test situations was unknown. The boundary conditions of the test situations are in between rigid and free in both experiments. The effect of the boundary conditions needs further investigation. The appropriate mesh size for an acoustic numerical model is widely investigated. Realistic results are obtained with a mesh of at least 6 to 10 elements per wavelength. In the direct sound transmission model, the sound in the sending room must be diffuse. The diffuse sound field can be created with a mass sound source that sends pressure waves. The vibration reduction index model is excited by a sinusoidal peak force, similar to the excitation in the measurement setup.

In order to develop an accurate numerical sound transmission model, the effect of several design parameters must be investigated. The parameters of concern are:

- The modelling of the CLT panels: one element or layers
- The boundary conditions of the direct sound transmission model: rigid or free
- The influence of the material properties of CLT on the direct sound transmission
- The boundary conditions of the vibration reduction index model: free hanging panels or on hold-downs
- The modelling of the connectors and the effect on the vibration reduction index
- The effect of an elastic interlayer on the vibration reduction index

# 5

## SENSITIVITY ANALYSIS

In the previous chapter, two numerical sound transmission models were constructed. Namely, the direct sound transmission model and the vibration reduction index model. In this chapter, the sensitivity of important design parameters will be evaluated to answer the following question; *Which material and design parameters have the most influence on the sound transmission?* A sensitivity analysis is a study into the variability of the output of the models due to variability in the input parameters. It is a useful tool to identify the most influential parameters. The direct sound transmission model will be used to determine the effect of different modelling techniques of the CLT element, the boundary conditions and the material properties of the CLT. The vibration reduction index model will be used to determine the effect of the boundary conditions, the effect and type of the interlayer and the type and number of connectors.

### 5.1. MODELING THE CLT ELEMENT

Two different methods are investigated to determine the effect of the type of modelling of the CLT panels, both methods are visualized in figure 5.1. The 5-ply CLT panels are 3\*3 m and have a thickness of 175 mm. The first method is to model the elements as one solid element. The second method is to model the five CLT lamellas as individual elements. For both methods, the CLT panels are assumed to be without any gaps between the lamellas or knots in the wood.

Modelling the CLT as one solid element is a very simplified version of a CLT element. The material properties are assumed to be the average of the material properties of the single layers. The material properties used for the solid model of the CLT element are given in table 4.3

The second method is to create a CLT element where all the individual layers are modelled, each layer is 35 mm. In this way, it is possible to assign a local coordinate system to each panel. The in-plane x- and y-direction of the layers are alternated to create the crosswise CLT panel to imitate the cross-wise lamellas of a CLT element. The individual panels are assumed to be fully bonded. This means there is no relative displacement possible between the layers and the influence of the glue layer is in this way neglected. The material properties used for the layered model of the CLT element are given in table 4.3.

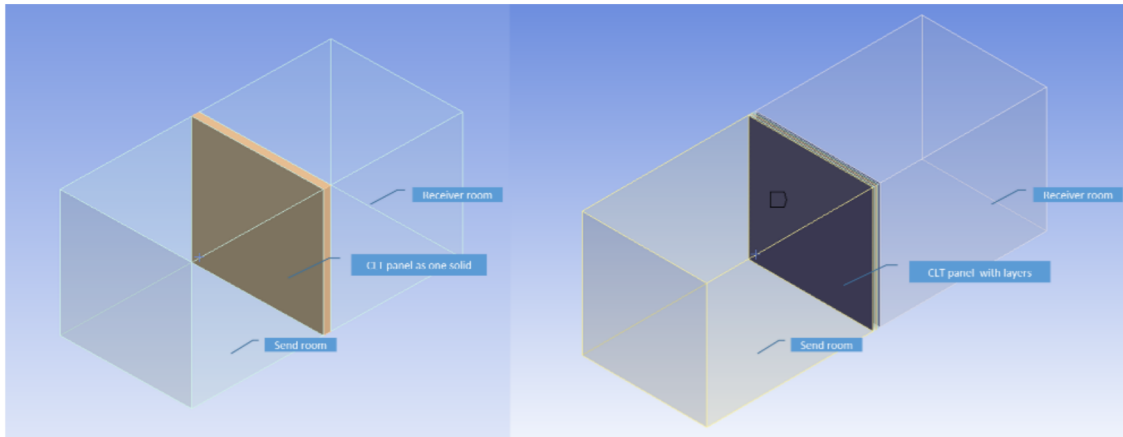


Figure 5.1: Geometry of the direct sound transmission model with on the left the model with a single solid element and on the right the model with the individual timber lamellas

Input parameter	Quantity	Unit	One element	Layered elements
Density	$\rho$	kg/m <sup>3</sup>	500	500
Young's modulus x-direction	$E_x$	MPa	6720	11000
Young's modulus y-direction	$E_y$	MPa	4580	300
Young's modulus z-direction	$E_z$	MPa	4580	300
Poisson ratio x	$\nu_x$	-	0,3	0,3
Poisson ratio y	$\nu_y$	-	0,4	0,4
Poisson ratio z	$\nu_z$	-	0,4	0,4
Shear stiffness xy	$G_{xy}$	MPa	650	650
Shear stiffness xy	$G_{xy}$	MPa	65	65
Shear stiffness xy	$G_{xy}$	MPa	650	650
Internal loss factor	$\eta$	-	0,08	0,08

Table 5.1: CLT element material properties used in FEM for the solid element and layered element (175 mm 5-ply element) [38]

The results of the two methods for a 5-ply panel of 175 mm are shown in figure 5.2. In appendix D the results for a 3-ply, 7-ply and 9-ply element are also shown. The average absolute difference between the measurements and layered models is maximal 3 dB. For solid models, the average absolute difference is maximal 5 dB. The maximal absolute difference is always equal or smaller for a layered model. Therefore in all future models, the individual lamellas will be modelled.

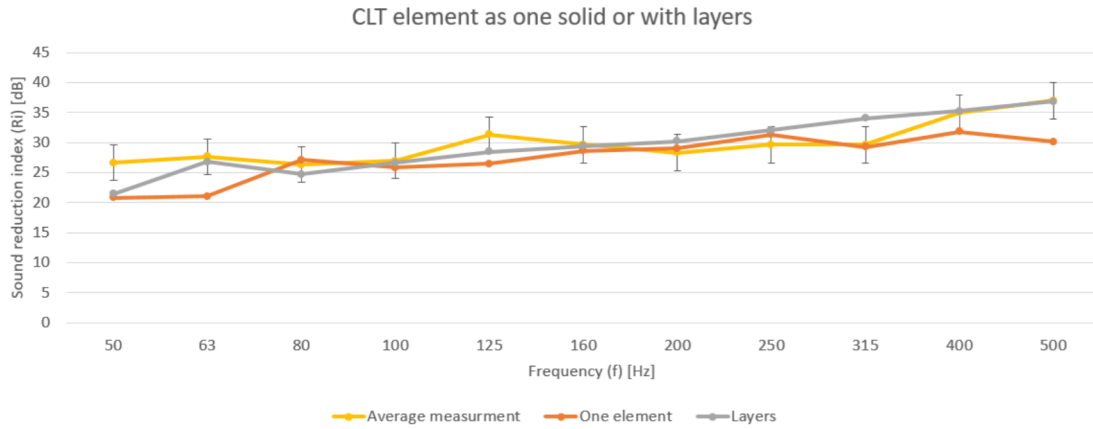


Figure 5.2: Results of the sound reduction index of a 175 mm solid CLT element and a layered 175 mm solid 5-ply CLT element with the material properties as stated in table 5.1 compared to three measurements [26]

## 5.2. BOUNDARY CONDITIONS DIRECT SOUND TRANSMISSION MODEL

The influence of the boundary conditions on the sound reduction is investigated. Two options are investigated and shown here: a rigid boundary and a free boundary. The largest changes are observed in the frequency range below 50 Hz, but also for the higher frequencies the differences are significant. The overall trend of the rigid boundary condition shows higher peaks and dips than the trend of the free boundary conditions. The locations of the peaks and dips of the rigid boundary conditions show more similarity with the measurement results than the locations of the peaks and dips of the free boundary conditions. Therefore in further investigations, a rigid boundary condition will be considered. The differences in the sound reduction index in the low-frequency range are significantly influenced by changes in the boundary conditions at the edges of the element.

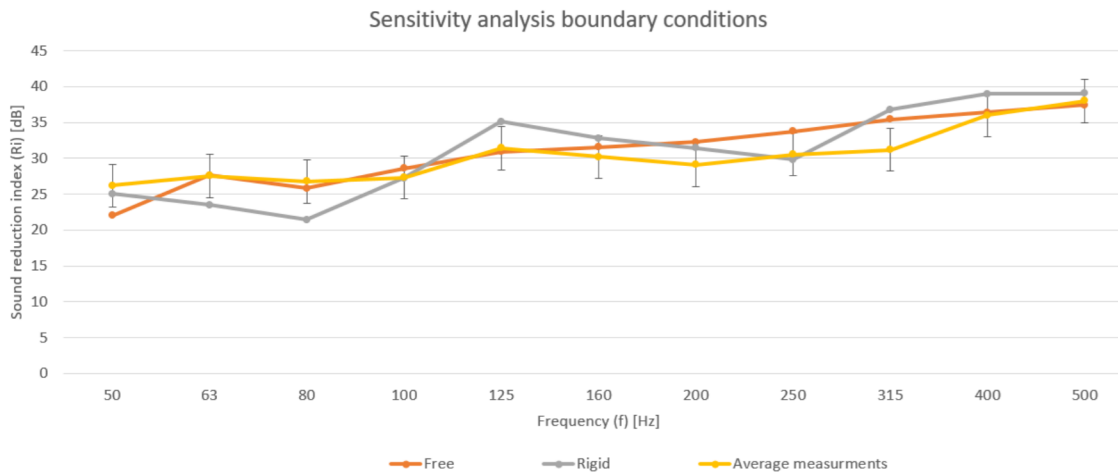


Figure 5.3: Sensitivity analysis of the boundary conditions compared to the average measurement results, the material properties used are given in table 5.1

### 5.3. CLT MATERIAL PARAMETERS

The influence of the material properties of the CLT elements is further investigated. The correlation between the input parameters was neglected for the simplicity of this analysis. The output of the model is the sound pressure level in the send and receiver room. With post-processing, the sound reduction index can be calculated from these results. The individual lamellas are modelled and rigid boundary conditions are applied along the perimeter of the CLT panel, conditions which were found to provide the best agreement with the experimental results.

Material properties that are investigated are the density, Young's modulus, poisson ratio, shear modulus, and damping ratio. As timber is an anisotropic material the input parameters Young's modulus, poisson ratio, and shear stiffness are investigated separately for the x, y, and z directions.

Input parameter	Quantity	Dimension	Begin properties	Investigated range
Density	$\rho$	kg/m <sup>3</sup>	500	300-600
Young's modulus x-direction	Ex	MPa	11000	7000-13000
Young's modulus y-direction	Ey	MPa	300	300-3000
Young's modulus z-direction	Ez	MPa	300	3-300
Poisson ratio x	vx	-	0,3	0,001-0,9
Poisson ratio y	vy	-	0,4	0,001-0,9
Poisson ratio z	vz	-	0,4	0,001-0,9
Shear stiffness xy	Gxy	MPa	650	-
Shear stiffness xy	Gxy	MPa	65	-
Shear stiffness xy	Gxy	MPa	650	-
Internal loss factor	$\eta$	-	0,08	0-1

Table 5.2: Begin material properties values for the sensitivity analysis

To check the influence of a single parameter the value of only this parameter is changed. The values of all the other parameters remain the same. The values used for these parameters are the start values which are given in table 5.2. The values are based upon values found in literature [66]. The lamellas are modelled individually as this resulted in more accurate results. The boundary condition used for the parameter analysis is a rigid connection along the edges of the test element. The results are given here for each parameter. For reference, the average of the three measured values is included in all the figures. The margins of errors included are 3 dB.

5.3.1. DENSITY

According to the literature by doubling the mass the sound reduction will be 5 á 6 dB higher in the mass controlled region. The density has a significant influence on the amount of sound reduction through the element however a difference in density does not show differences in deviations in the trend as can be seen in figure 5.4. The differences between 300 kg/m<sup>3</sup> and 600 kg/m<sup>3</sup> are indeed around 6 dB from 80 to 125 Hz.

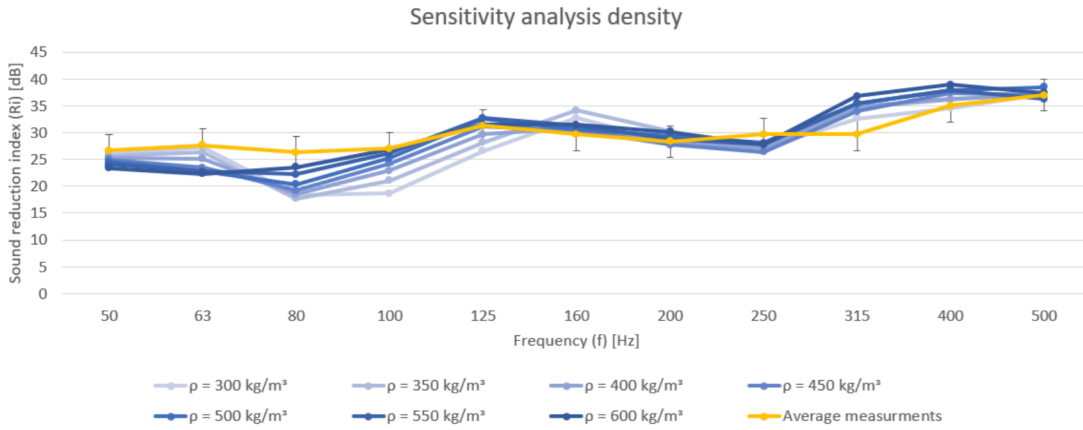


Figure 5.4: Sensitivity analysis of the density compared to the average measurement results

5.3.2. YOUNG'S MODULUS

The influence of the Young's modulus in the x-direction is investigated in the range of 7000 to 13000 MPa. The results are shown in figure 5.5. It can be concluded that this parameter is of little influence on the sound reduction in the frequency range up to 500 Hz. The largest changes are at 50, 80, and 500 Hz where the maximal difference is 4 dB between an Ex of 7000 MPa and an Ex of 13000 MPa. In all the other frequencies the differences are within a range of 1 dB.

The stiffness-controlled region is below 50 Hz. Increasing Young's modulus in the x-direction results in a small increase of the sound reduction in this range. An increase of 1000 MPa results in an around 0,2 dB higher sound reduction.

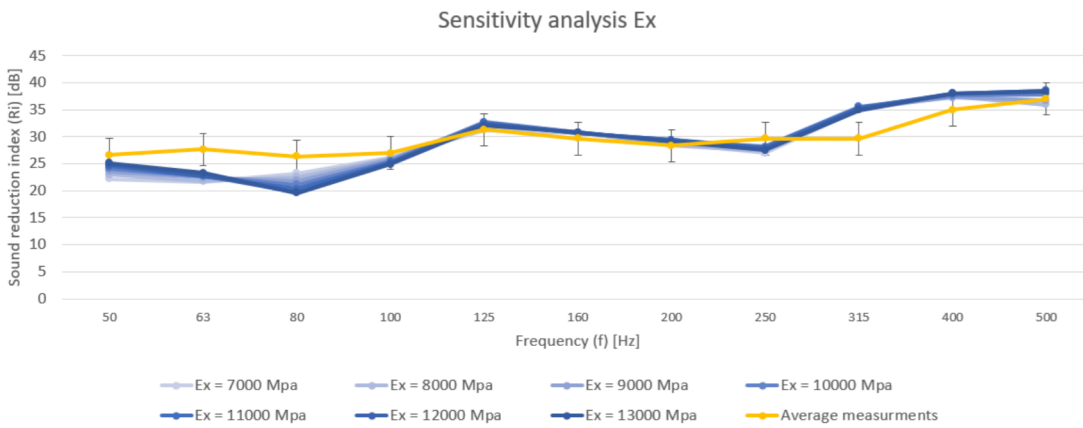


Figure 5.5: Sensitivity analysis of the Young's modulus in the x-direction compared to the average measurement results

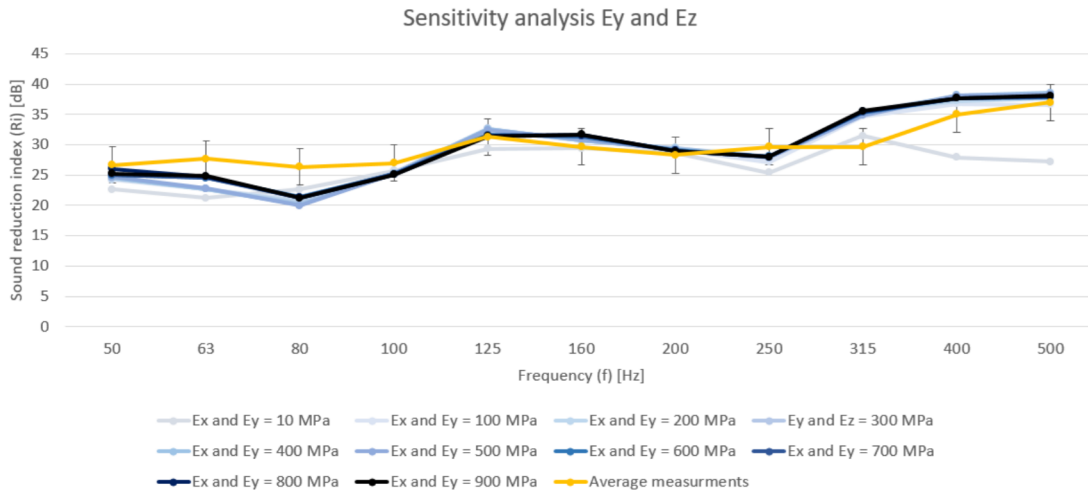


Figure 5.6: Sensitivity analysis of the Young's modulus in the y- and z-direction compared to the average measurement results

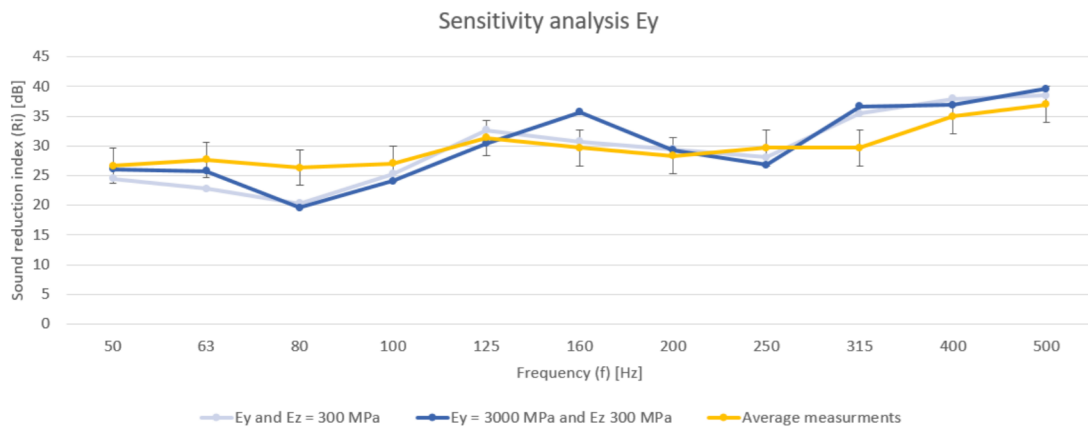


Figure 5.7: Sensitivity analysis of the Young's modulus in the y-direction compared to the average measurement results

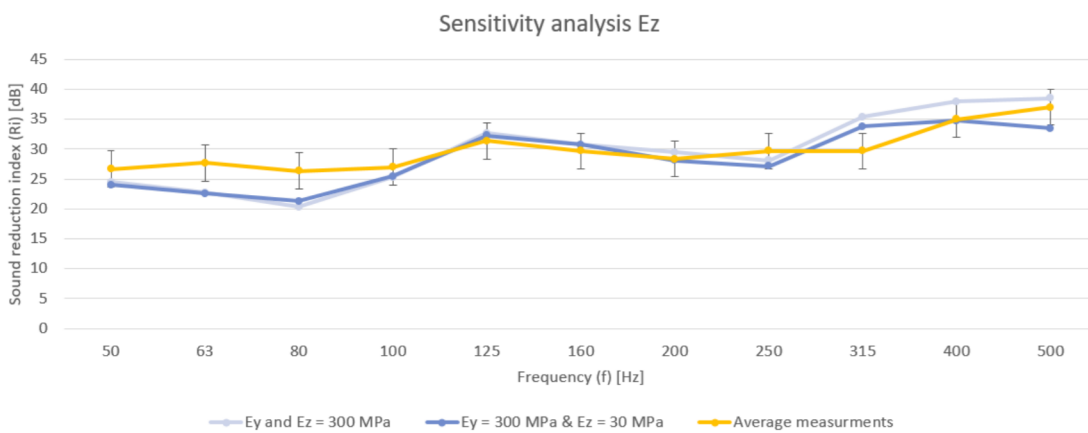


Figure 5.8: Sensitivity analysis of the Young's modulus in the z-direction compared to the average measurement results



The influence of the Young's modulus in the y and z direction is investigated in the range of 10-500 MPa. It was first assumed that the Young's modulus is equal for the y- and z-direction. From figure 5.6 it can be concluded that this parameter is of influence on the sound reduction in the lower frequency range. The largest changes are above 250 Hz. The Young's modulus is of influence for the location of the coincidence dips in the sound reduction. The lower the Young's modulus the lower the frequency of this dip.

The influence of the Young's modulus in the y and z direction is also investigated separately. First, the Young's modulus in the y-direction, see figure 5.7. Increasing the  $E_y$  is of little influence in the lower frequency range. Second is the Young's modulus in the z-direction, see figure 5.8. The investigated range of the  $E_z$  is from 50 - 3 MPa whilst the  $E_y$  is constantly 300 MPa. The lower the  $E_z$  becomes the lower the frequencies of the resonance dips become. Above the 30 MPa, the differences in the lower frequency range are limited but below 10 MPa the resonance dips are in the frequency range of interest.

### 5.3.3. POISSON'S COEFFICIENT

The Poisson's coefficient gives a ratio between the deformation of a material in the direction perpendicular to the direction of loading. For the direct sound transmission, the displacement in the direction of the separating element is of influence. Therefore the influence of Poisson's coefficient on the direct sound reduction is expected to be little. What can be seen in figure 5.9 is that Poisson's coefficient indeed has little to no influence on the sound reduction. Three different Poisson coefficients were used in the model. The results show little to no changes due to changes in Poisson's coefficient. For this analysis, the Poisson's coefficients in x, y, and z-direction were set equal.

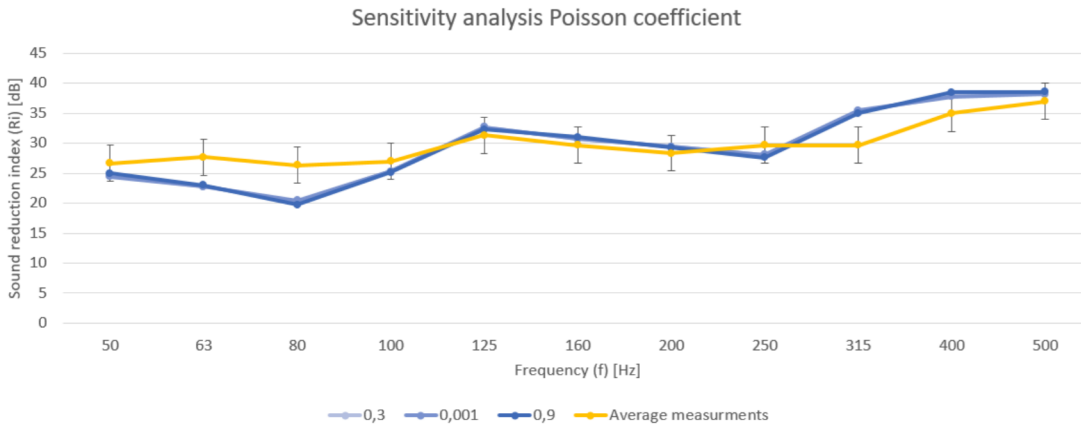


Figure 5.9: Sensitivity analysis of the Poisson's coefficient compared to the average measurement results

### 5.3.4. INTERNAL LOSS FACTOR

Since the internal loss factor is above 3% the internal loss factor is assumed to be the only significant type of damping. The damping ratio is of influence on the sound transmission, which can be seen in figure 5.10. A low damping ratio results in larger dips in the sound insulation, whilst a high damping ratio dampens these dips. A damping ratio of 1 smoothens out all the dips. The largest differences can be observed at the largest dip, which is around 80 Hz. The internal loss factor of timber is around 8% for the lower frequency range. But higher damping ratios (0,2 and 0,4) show results that match better with the measurements.

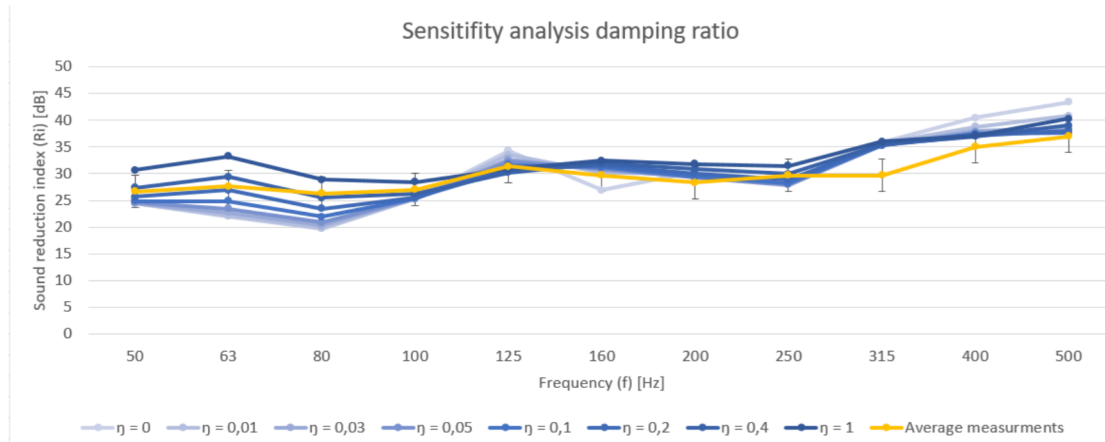


Figure 5.10: Sensitivity analysis of the internal loss factor compared to the average measurement results

### 5.4. BOUNDARY CONDITIONS OF THE VIBRATION REDUCTION INDEX MODEL

Rotoblaas assumed that the measurement setup creates a situation that is not influenced by the boundary conditions. The boundary conditions were assumed to be fully free. In the test situation, the panels are connected to concrete blocks by hold-downs. The hold-downs are located near the side edges of the panel. To mimic the connections the outer bottom corners of the CLT panels are given a zero displacement.

The results of the free model and the model with zero displacements at the outer bottom corners are in the figures 5.11, 5.12 and 5.13. It can be seen that the results are similar for a model with free edges and a model with hold-downs. The differences are generally within the range of 5 dB, but with a few outliers with differences up to 15 dB. The average difference is within 3 dB. Therefore it is concluded that in the frequency range of interest the effect of the hold-downs is not neglectable. The boundary conditions in the vibration reduction index models will be assumed to be free to comply with the regulations of the ISO standard.

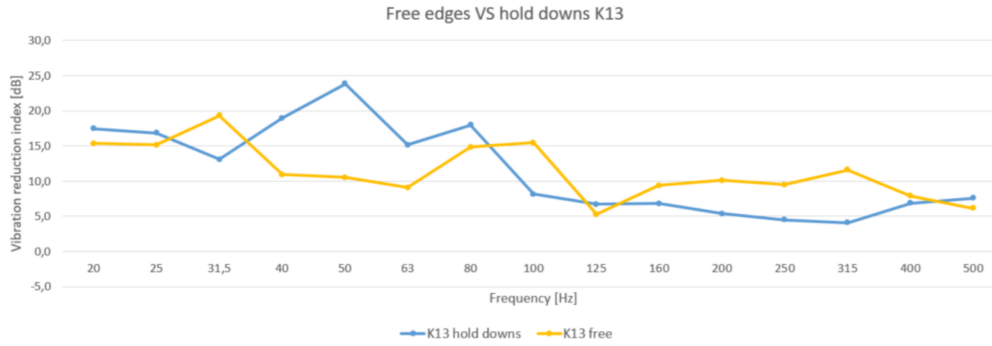


Figure 5.11: Results of the vibration reduction index K13 of a model with free edges and a model with hold downs

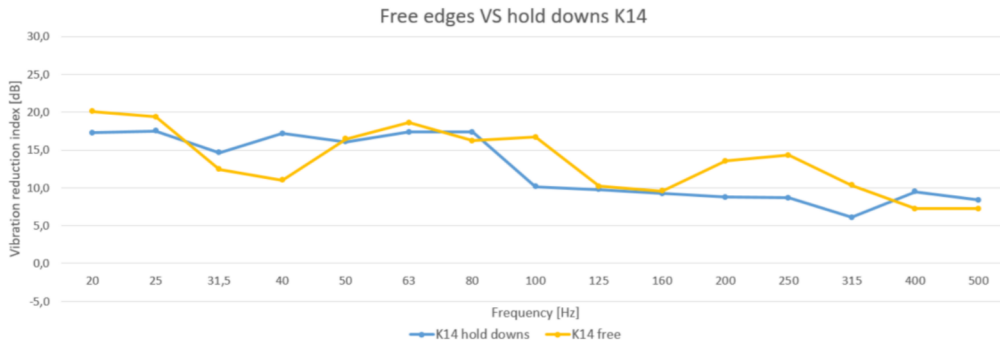


Figure 5.12: Results of the vibration reduction index K14 of a model with free edges and a model with hold downs

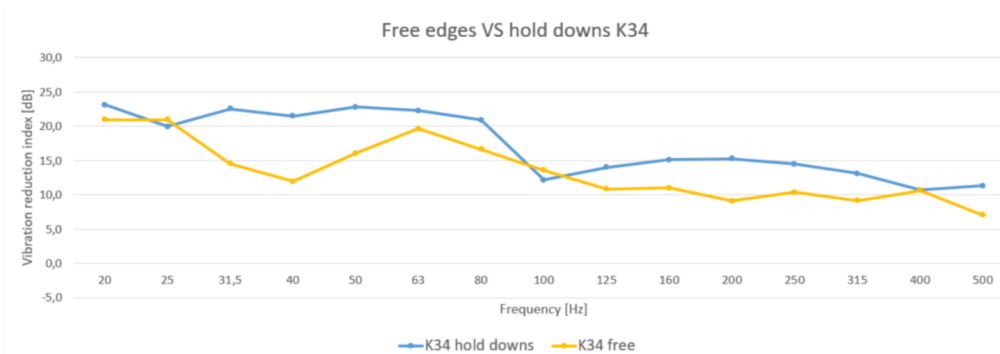


Figure 5.13: Results of the vibration reduction index K34 of a model with free edges and a model with hold downs

### 5.5. INTERLAYER IN THE VIBRATION REDUCTION INDEX MODEL

Interlayers are placed to reduce the sound transmission between panels. Here the results of a T-junction without an interlayer are compared to the results of a T-junction model with a construction sealing in between the panels. The results are shown in figure 5.17, 5.18 and 5.19. The material properties of the construction sealing are given in table 4.4. The effect of the interlayer is minimal in the low-frequency range. The differences above 20 Hz are all within the range of 5 dB.



Figure 5.14: Results of the vibration reduction index K13 of a model without an interlayer and a model with an interlayer



Figure 5.15: Results of the vibration reduction index K14 of a model without an interlayer and a model with an interlayer



Figure 5.16: Results of the vibration reduction index K34 of a model without an interlayer and a model with an interlayer

## 5.6. TYPE OF INTERLAYER IN THE VIBRATION REDUCTION INDEX MODEL

Different types of interlayers can be used. Two different types of material are used as an interlayer in the numerical model. The results of these two simulations are shown here in figure 5.17, 5.18 and 5.19. The material properties of the interlayers are given in table 4.4. The results show that the type of interlayer has very little influence on the vibration reduction index in the low-frequency range. The XYLO90 shows a slightly better sound reduction than the construction sealing, but the differences are all below 3dB.

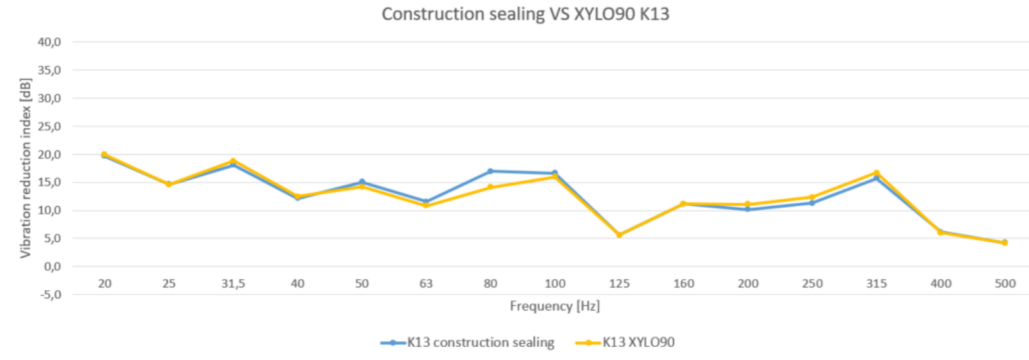


Figure 5.17: Results of the vibration reduction index K13 of a model with construction sealing as an interlayer and a model with XYLO90 as an interlayer

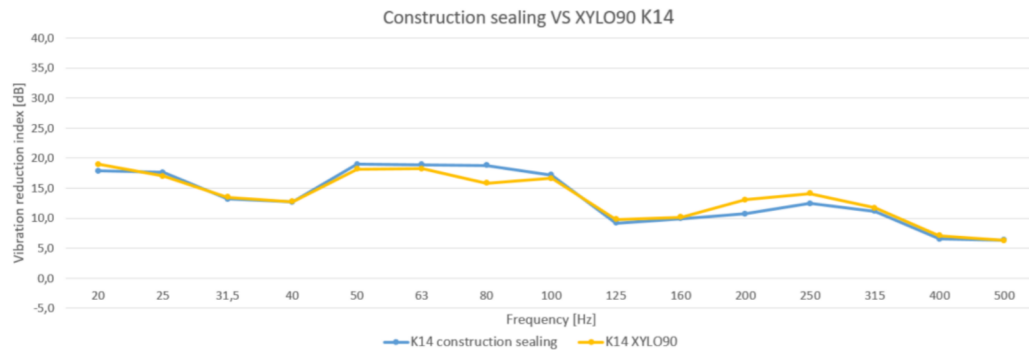


Figure 5.18: Results of the vibration reduction index K14 of a model with construction sealing as an interlayer and a model with XYLO90 as an interlayer

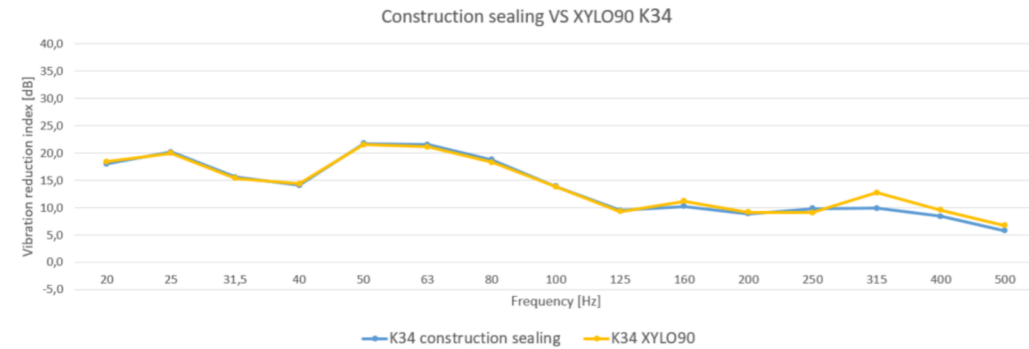


Figure 5.19: Results of the vibration reduction index K34 of a model with construction sealing as an interlayer and a model with XYLO90 as an interlayer

## 5.7. CONNECTORS

Based upon the amount of computational cost the bolts are not modelled in the final FE models. In the final model, the contact areas between the panels are assumed to be frictional contact regions. The CLT panels have a friction coefficient of 0,4 (timber to timber friction coefficient).

The effect of the connectors on the vibration reduction index could not be determined due to the large amount of computational capacity needed. This will be further discussed in Chapter 7.

## 5.8. CONCLUSION

In this chapter the most influential design and material parameters are investigated. It can be concluded that the modelling the individual layers is necessary to accurately capture the sound reduction of a CLT element. Modelling the individual timber lamellas with interchanging coordinate systems provides more accurate results than modelling a solid element where the material properties are based upon the average values of the individual lamellas. The higher the number of layers the larger the difference between the individual lamellas and the solid elements.

The effect of different material properties applied to the CLT elements in the numerical simulation was investigated with a sensitivity analysis. From the sensitivity analysis the following conclusions can be drawn:

- The Young's modulus in the x-direction has little influence on the sound reduction in the low-frequency range.
- In the low-frequency range the Young's modulus in the y and z-direction of the timber lamellas have a large influence on the location of the resonance induced dips in the sound reduction.
- The Poisson coefficient has little influence on the sound reduction in the low-frequency range.
- The density influences the amount of sound reduction but only after the stiffness controlled region. There the higher the density the higher the amount of sound reduction.
- The internal loss factor in cross-laminated timber is 8 % in the lower frequencies. The results of the sensitivity analysis show that the amount of sound reduction is dependent on the internal loss factor. An internal loss factor above 20 % shows results that are in better agreement with the measurements.
- The boundary conditions influence the stiffness controlled region, rigid boundaries results in a higher sound reduction in the stiffness controlled region than free boundaries. The trend of the sound reduction index in the low-frequency spectrum is more influenced by the boundary conditions than by the material properties.

Based on the sensitivity analysis of the material properties of CLT some properties are changed. The final values are given in table 5.4 and will be used in all future models. Some parameters showed only minor changes in the low-frequency range. For these parameters, the beginning values will be used. This is the case for Young's modulus in the x-direction, Poisson coefficient, shear stiffness and density. The Young's modulus in the y- and z-direction showed a large influence on the location of the coincidence dips in the low-frequency range. The first assumption that  $E_y = E_z$  seemed incorrect, as lowering Young's modulus in the z-direction showed better matching results. Therefore the  $E_z$  modulus is changed to 30 MPa. The internal loss factor  $\eta$  is the only type of damping considered in the model, all other types of damping are neglected (for example boundary losses). A larger internal loss factor resulted in more accurate results. Therefore a higher damping ratio of 0,2 is used in the models. With the use of the fitted values the results improved. The average absolute difference and the maximal absolute difference of both the begin values and the fitted values are compared in table 5.3.

	Begin values	Fitted values
Average absolute difference [dB]	3,4	1,6
Maximal absolute difference [dB]	6,4	4,6

Table 5.3: Comparison between the differences with the average measurements for the results of the numerical model with the begin values and the fitted values

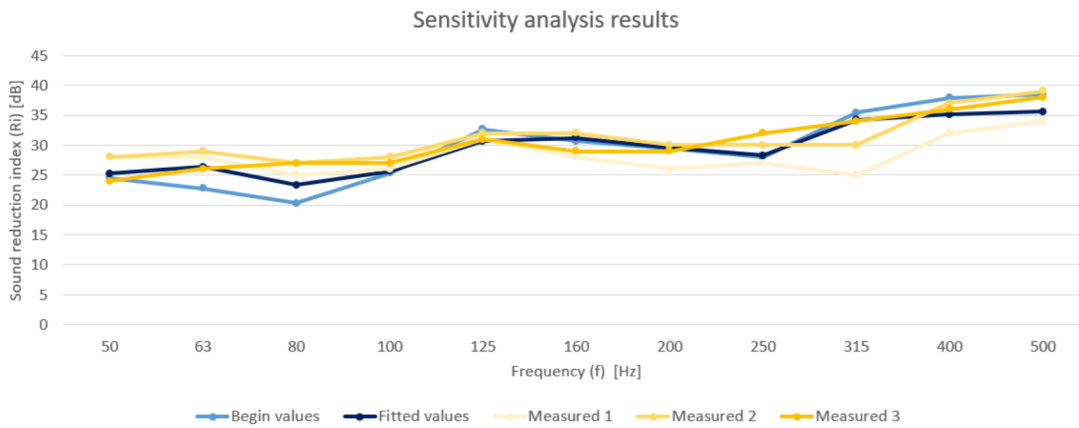


Figure 5.20: Results of the sensitivity analysis with the results of the begin values as given in table 5.2 and the results of the fitted values as given in table 5.4 compared to the three measurements

Input parameter	Quantity	Unit	Start value	Final value
Density	$\rho$	kg/m <sup>3</sup>	500	500
Young's modulus x-direction	Ex	MPa	11000	11000
Young's modulus y-direction	Ey	MPa	300	300
Young's modulus z-direction	Ez	MPa	300	30
Poisson ratio x	vx	-	0,3	0,3
Poisson ratio y	vy	-	0,4	0,4
Poisson ratio z	vz	-	0,4	0,4
Shear stiffness xy	Gxy	MPa	650	650
Shear stiffness xy	Gxy	MPa	65	65
Shear stiffness xy	Gxy	MPa	650	650
Internal loss factor	$\eta$	-	0,08	0,2

Table 5.4: Material properties of the CLT based upon the sensitivity analysis

The results of a T-junction without an interlayer are compared to the results of a T-junction model with a construction sealing in between the panels. The results are shown in figure 5.17, 5.18 and 5.19. The material properties of the construction sealing are given in table 4.4. The effect of the interlayer is minimal in the low-frequency range. The differences above 20 Hz are within the range of 5 dB.

Two different types of material are used as an interlayer in the numerical model. The results of these two simulations are shown in figure 5.17, 5.18 and 5.19. The material properties of the interlayers are given in table 4.4. The results show that the type of interlayer has little influence on the vibration reduction index in the low-frequency range. The XYLO90 shows a slightly better sound reduction than the construction sealing, but the differences are below 3 dB.





# 6

## RESULTS AND OBSERVATIONS

In this chapter the following question will be answered: *What is the difference between the amount of sound transmission calculated by a numerical model, measured results and the calculated sound transmission according to the ISO standards?* Two numerical models have been developed to obtain the flanking sound transmission between apartments. The aim is to validate these two models in order to calculate the flanking sound transmission between apartments. The first model is used for computing the level of direct sound transmission. The second model computes the vibration reduction index of a joint. The data of both models is required to quantify the amount of flanking sound transmission through a specific path.

### 6.1. RESULTS AND OBSERVATIONS DIRECT SOUND TRANSMISSION MODEL

This section presents the data gathered by the numerical direct sound transmission model. This model can be used to determine the sound reduction through a bare CLT element as well as the effect of additional linings. The individual lamellas of the CLT are modelled and the material properties are based on the sensitivity analysis. The boundary conditions of the CLT element are rigid. The boundaries of the additional layers are assumed to be free.

#### 6.1.1. BARE CLT ELEMENT

For both the rooms the average acoustic pressure and the A-weighted average sound pressure level, as shown in figure 6.1, are determined. It can be seen that the sound source creates a diffuse sound field in the sending room. The average A-weighted sound pressure level and the acoustic pressure are computed for each frequency in the 1/3 octave band.

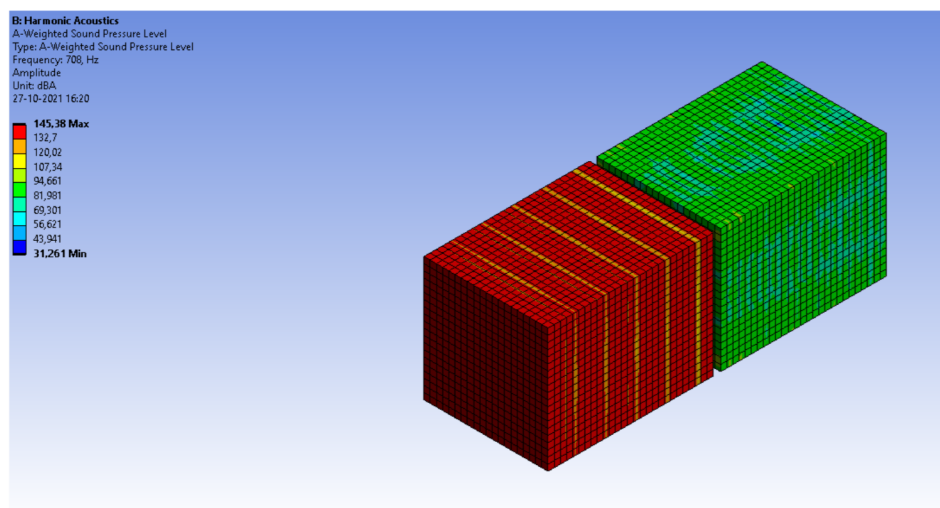


Figure 6.1: A-weighted sound pressure level in the send (left) and receiver room (right) at 708 Hz

The results are exported to excel for post-processing. The sound reduction index is the difference between the acoustic pressure in the send and receiver room and an additional correction term. The correction term takes into account the amount of absorption in the receiver room (A) and the dimensions of the tested element(S). The absorption coefficient used can be found in Appendix C. The following equation is used:

$$R = L_{send} - L_{receiver} + 10 * \text{LOG}\left(\frac{S}{A}\right) \quad (6.1)$$

with:

$$L_{send} = 10 * \text{LOG}\left(\frac{P_{send}}{20 * 10^{-12}}\right) \text{ and } L_{receiver} = 10 * \text{LOG}\left(\frac{P_{receiver}}{20 * 10^{-12}}\right) \quad (6.2)$$

In figure 6.2 the results of the three measurements, the sound reduction according to the EN 12354-1 and the final results of the direct sound transmission model are shown. The material properties used in the numerical model are given in table 4.3. These material properties are based upon the sensitivity analysis. The numerical trend of the results of the direct sound reduction through the 5-ply 175 m thick CLT panel is in agreement with the trend of the measurement results.

	ISO 12354	Numerical model
Average absolute difference [dB]	4	2
Maximal absolute difference [dB]	7	5

Table 6.1: Comparison between the differences with measurements for the results according to the ISO standard and the results of the numerical model

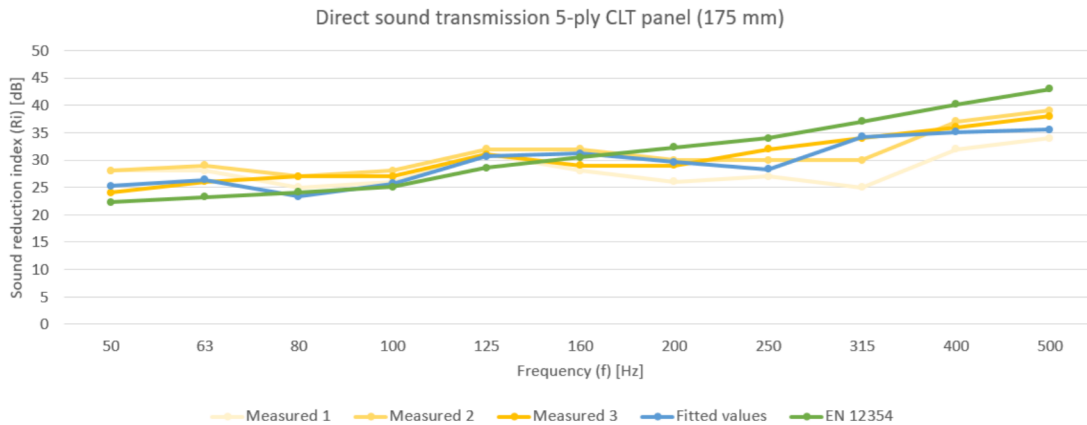


Figure 6.2: Direct sound transmission for a 5-ply (175mm) element: 3 different measurements, according to the EN 12354-1 and results of the numerical model for direct sound transmission with the material properties that are based upon the sensitivity analysis

## OBSERVATIONS

- The measurement results show significant differences between the three different measurements. Around 315 Hz the differences are up to 9 dB. For all other frequencies, the differences are within a 5 dB range.
- The numerical model for a bare CLT element estimated a similar trend of sound reduction when compared to the measurement results. The coincidence critical frequency of the CLT 175 mm panel is around 80 Hz. The coincidence dip is reproduced by the FE model. The difference between the average measurement value and the numerical value is within 3 dB for all frequencies except for 315 Hz. At 315 Hz the difference with the average measurement value is 5 dB.
- The difference between the sound reduction according to the ISO standard and the measured data is within the range of 5 dB. An exception is 315 Hz, where the difference is 7,5 dB. The results of the numerical model show more resemblance with the measured values than the results of the ISO standard.

### 6.1.2. ADDITIONAL LINING

The sound transmission through a CLT panel with additional linings is calculated for two different cases. The additional lining in the first case is 13 mm rubber and 38 mm concrete on a bare 175 mm CLT element. The second case is a bare 175 mm CLT element with 35 mm fibreglass and 32 mm Gypsum. The Gypsum panels are attached to the CLT element with Z channels, these channels are not included in the model. In figure 6.3 and 6.4 the results of respectively the first and the second case measurements, sound transmission according to the EN 12354-1 and the final results of the direct sound transmission model are shown. The material properties used in the numerical model are given in table 4.2 and 4.3.

#### CASE 1 - 131 MM CLT + 13 MM RUBBER + 38 MM CONCRETE

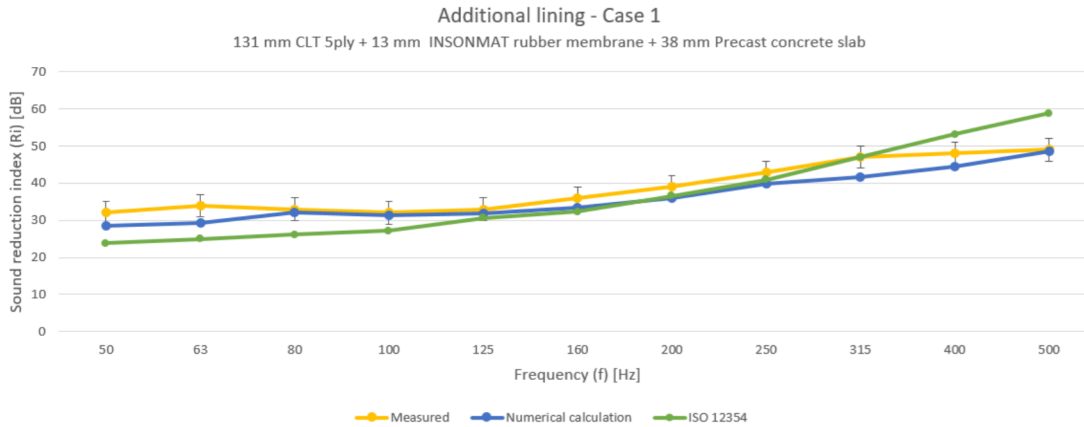


Figure 6.3: Direct sound reduction of 131 mm CLT (5-ply) + 13 mm Rubber membrane + 38 mm Precast concrete

	ISO 12354	Numerical model
Average absolute difference [dB]	5	3
Maximal absolute difference [dB]	10	5

Table 6.2: Comparison between the differences with measurements for the results according to the ISO standard and the results of the numerical model

#### OBSERVATIONS

- Compared to the measurement results the numerical model is able to estimate a similar trend of sound reduction, the average difference is within the range of 3 dB. The maximal difference between the measurement of case 1 and the numerical calculation is within the range of 5 dB. Overall the model gives a small underestimation of the amount of sound reduction.
- The difference between the sound reduction according to the ISO standard and the measured data is within the range of 10 dB. The average difference is 5 dB. The code is underestimating the amount of sound reduction in the frequencies below 315 Hz. After 315 Hz the code starts to largely overestimate the amount of sound reduction.
- The results of the numerical model show more resemblance with the trend of the measured values than the results of the ISO standard. Also, the average and maximal differences are smaller for the numerical model.

## CASE 2 - 175 MM CLT + 25 MM FIBRE GLASS + 32 MM GYPSUM

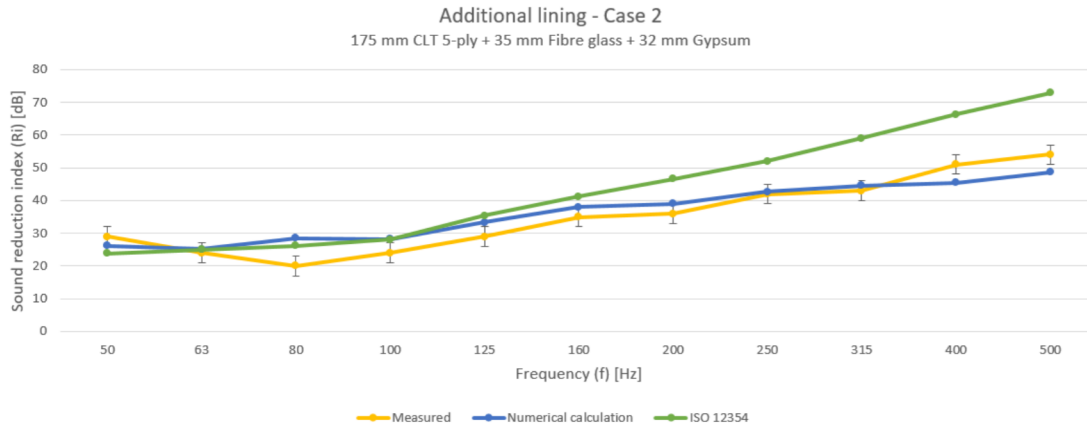


Figure 6.4: Direct sound reduction of 175 mm CLT (5-ply) + 35 mm Fibre glass + 32 mm Gypsum

	ISO 12354	Numerical model
Average absolute difference [dB]	9	4
Maximal absolute difference [dB]	19	8

Table 6.3: Comparison between the differences with measurements for the results according to the ISO standard and the results of the numerical model

## OBSERVATIONS

- The numerical model was not able to estimate the resonance frequency of the build-up around 80 Hz. Except for the missing dip around the resonance frequency, the average trend is similar to the measurement results. The average difference is still within the range of 4 dB. The maximal difference between the measurement and the numerical calculation is 8 dB and at the resonance frequency.
- The ISO standard did estimate a dip in the sound reduction value due to the panel resonance. The resonance frequency is calculated to be around 100 Hz, instead of the 80 Hz measured. The difference between the sound reduction according to the ISO standard and the measured data is within the range of 19 dB. The average difference is 9 dB. The code is overestimating the amount of sound reduction, especially above the resonance frequency.
- The results of the numerical model show more resemblance with the trend of the measured values than the results of the ISO standard. Also, the average and maximal differences are smaller for the numerical model.

## 6.2. RESULTS AND OBSERVATIONS VIBRATION REDUCTION INDEX MODEL

This section presents the data gathered by the numerical vibration reduction index model. With this model, the vibration reduction of a junction can be determined. The deformation of the junction due to the load vector can be seen in figure 6.5. The individual lamellas of the CLT are modelled and the material properties are based on the sensitivity analysis. The boundaries of the junction are free and the contact between the different panels is fictionally bonded.

The numerical simulations determine the average directional velocity of different measurement points on the panels. For each frequency, in the 1/3 octave band, the average directional velocity of different measurement points is computed. These results are imported to excel for post-processing to calculate the vibration reduction index values from the numerical results. The following equation is used to calculate the vibration reduction index:

$$K_{ij} = D_{v,ij} + 10 * \text{LOG}\left(\frac{l_{ij}}{\sqrt{a_i * a_j}}\right) \quad (6.3)$$

$$a = \frac{2,2 * \pi^2 * S}{c_0 * T_s} * \sqrt{\frac{f_{ref}}{f}} \quad (6.4)$$

$$D_{v,ij} = 10 * \text{LOG}\left(\frac{v_i^2}{v_j^2}\right) \quad (6.5)$$

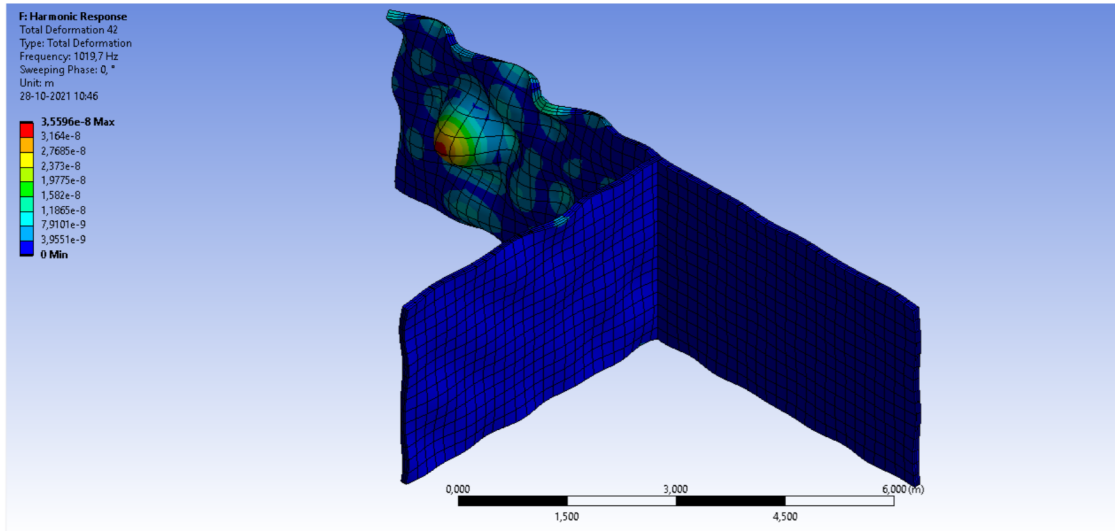


Figure 6.5: Deformation of the T-junction under the excitation load on panel 1

6.2.1. BARE JUNCTION

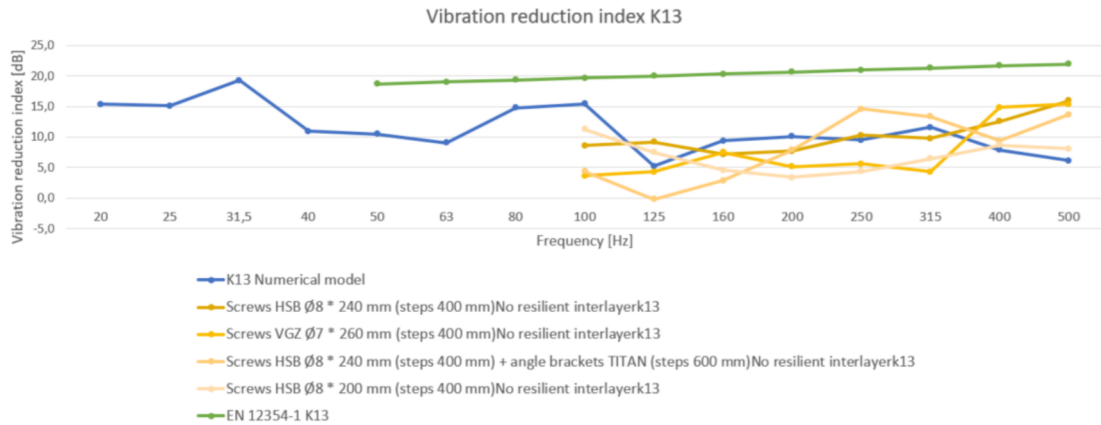


Figure 6.6: Vibration reduction index K13 for a 3-ply (100mm) T-junction without interlayer: 4 different measurements, according to the EN 12354-1 and results of the numerical model

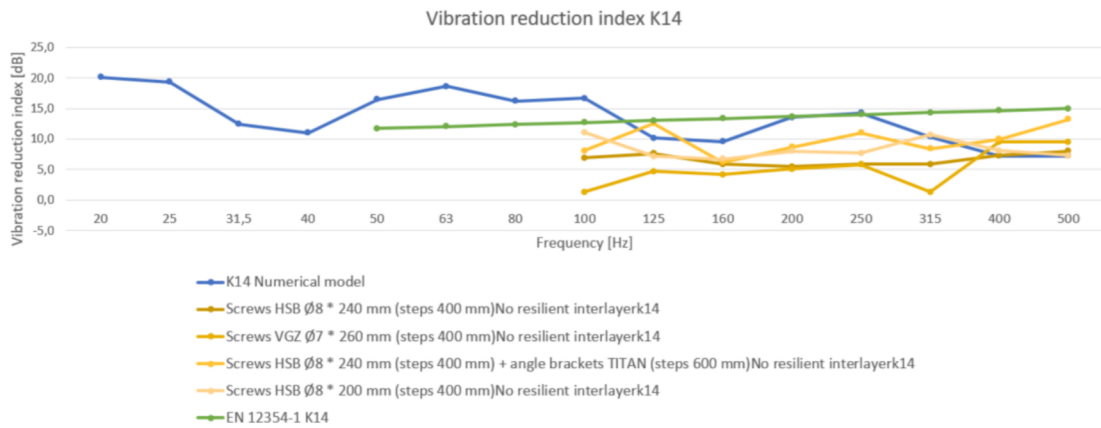


Figure 6.7: Vibration reduction index K14 for a 3-ply (100mm) T-junction without interlayer: 4 different measurements, according to the EN 12354-1 and results of the numerical model

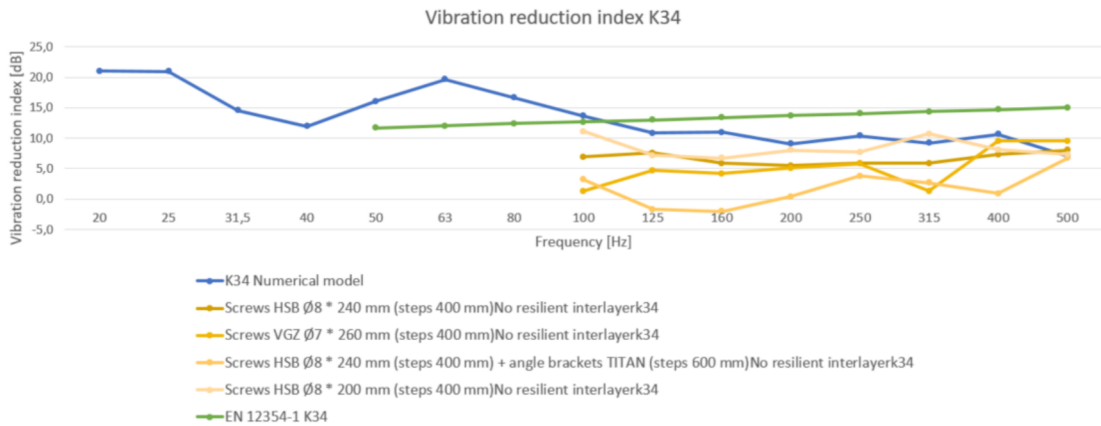


Figure 6.8: Vibration reduction index K34 for a 3-ply (100mm) T-junction without interlayer: 4 different measurements, according to the EN 12354-1 and results of the numerical model



In figure 6.6, 6.7 and 6.8 the results of the vibration reduction indices are compared to the measurement results and the vibration reduction index according to the EN 12354.

#### OBSERVATIONS

- The differences between measurements of the vibration reduction indices are up to 10 dB per frequency. Indicating the significant influence of the type and number of connectors.
- The ISO 12354 largely overestimates the vibration reduction index. This is the case for all three different paths.
- The K14 and K34 are symmetrical paths, in the case of symmetrical connectors on both sides, the results should be equal. The results of the K14 and K34 of the numerical model are indeed similar. This shows that the amount of measurement points used is enough to create results that are not significantly influenced by the effect of local variations in the material.
- The results of the numerical model are more in the range of the measurements than the results according to the ISO 12354. The results of the model are still on the higher side of the measurement results, especially compared to the junction also including angle brackets.

6.2.2. JUNCTION WITH ELASTIC INTERLAYER

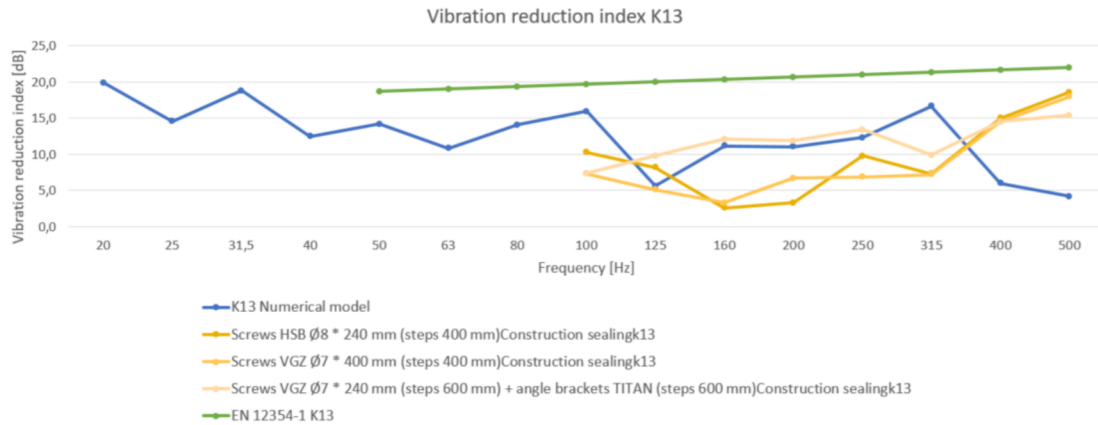


Figure 6.9: Vibration reduction index K13 for a 3-ply (100mm) T-junction with interlayer: 3 different measurements, according to the EN 12354-1 and results of the numerical model

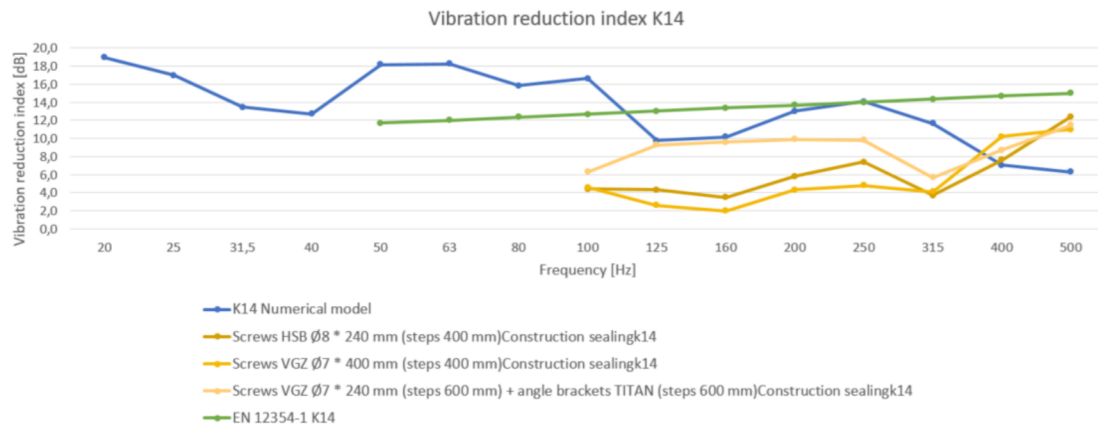


Figure 6.10: Vibration reduction index K14 for a 3-ply (100mm) T-junction with interlayer: 3 different measurements, according to the EN 12354-1 and results of the numerical model

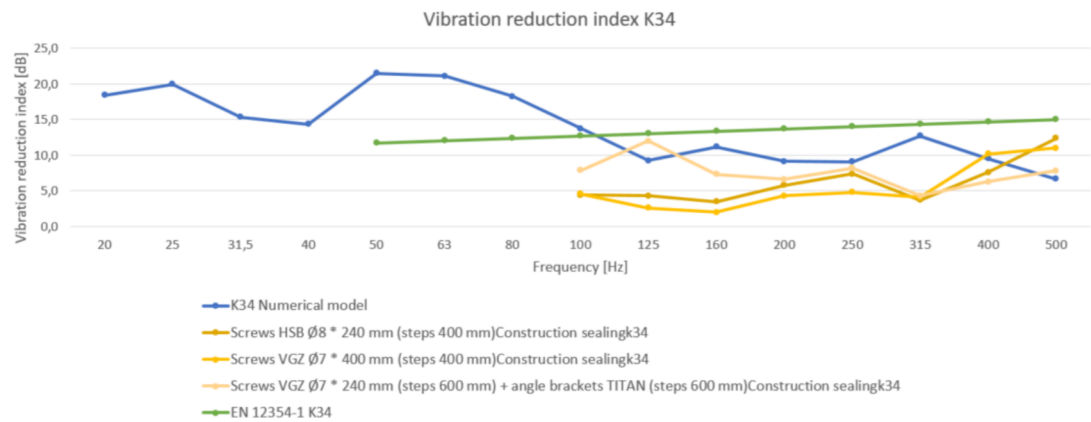


Figure 6.11: Vibration reduction index K34 for a 3-ply (100mm) T-junction with interlayer: 3 different measurements, according to the EN 12354-1 and results of the numerical model

In figure 6.9, 6.10 and 6.11 the results of the vibration reduction indices are compared to the measurement results and the vibration reduction index according to the EN 12354 without an interlayer, as the standard does not include the effect on the interlayer.

#### OBSERVATIONS

- The differences between measurements of the vibration reduction indices with interlayer are up to 6 dB per frequency which is less than for the junctions without interlayer.
- The ISO 12354 largely overestimates the vibration reduction index, even now compared to junctions with an interlayer. This is the case for all three different paths.
- The results of the K14 and K34 of the FE models with an interlayer are again similar. So, in models with interlayer, the results are also not significantly influenced by the effect of local variations in the material.
- The variance in measurements is smaller in the case of junctions with interlayer than in the case of junctions without interlayer. Indicating that the use of an elastic interlayer reduces the influence of the type of connector on the vibration reduction index.
- The results of the model with interlayer are also more in the range of the measurements than the results of the ISO 12354.

### 6.3. CONCLUSION

The difference between the amount of sound transmission calculated by a numerical model and measured results and the difference between calculated sound transmission according to the ISO standards and measurement results are compared. Overall it can be concluded that the results of the numerical models are more in line with the measurement data.

The differences between the numerical direct sound model and the three measurements are smaller than the differences between the sound transmission according to the ISO standard and the measurements. Below 125 Hz the ISO standard underestimates the sound reduction Hz and above 125 Hz it overestimates the sound reduction. The numerical model estimates the sound transmission within a range of 3 dB which was concluded to be an appropriate range since the difference of 3 dB is almost not noticeable by a person. The difference between the ISO standard and the measurements was in the range of 5 dB. These differences are larger and more noticeable by a resident.

Whereas the EN 12354 overestimates the vibration reduction index the numerical model more accurately estimates the vibration reduction index. This is the case for both the T-junction with and without elastic interlayer. Even though the connection between the T-junctions elements is modelled with frictional contact regions and not with connectors the results are more accurate than the estimation of the vibration reduction index of a T-junction with connectors by the ISO standard.

The effect of an elastic interlayer in the low-frequency range is limited, the differences are within the range of 5 dB. Below 20 Hz the differences become larger but these frequencies can not be heard by humans. The type of interlayer does not have a large influence on the vibration reduction index in the low frequencies. The differences between the construction sealing and the XYLO90 are all below 3 dB.

# 7

## DISCUSSION

This chapter focuses on the results and observations presented in Chapter 6. Two numerical models, which are presented in chapter 4, are used to estimate the amount of sound reduction. The influence of several materials and design parameters on the results was investigated and the results of the final models were compared to empirical data and the sound reduction according to the ISO 12354 in the sensitivity analysis in chapter 5. The most important observations and results are discussed here. There are several points of discussion.

Throughout the research and the modelling, several assumptions and choices were made. These assumptions can influence the results. The influence of several assumptions might be significant and will therefore be discussed in more depth as the assumptions influence the reliability of the results.

### 7.1. DIRECT SOUND TRANSMISSION MODEL

#### GEOMETRY

CLT is an orthotropic and layered material, therefore there is not one coincidence frequency but a coincidence region. The coincidence region of CLT elements is located in the low-frequency range. A model with the CLT panels modelled as solid elements is not able to capture this coincidence region. Modelling these individual layers will therefore improve the accuracy of the models. The results presented in appendix D and the sensitivity analysis in Chapter 5 showed that indeed a layered model resulted in more accurate results than a solid element model.

A CLT element with a higher number of layers acts more as an isotropic material since the bending stiffness of the primary axes become more equal. Therefore it was assumed that the higher the number of layers the smaller the differences would be between a layered model and a solid model. The results in appendix D showed the exact opposite. This implies that a panel with a higher number of layers might act as a more isotropic material but the effect of the layers on the coincidence region becomes more important.

The geometry of the model was chosen to be in line with the measurement setup. The final results of the numerical model should be independent of the size of the test elements since there is a correction term that corrects the results for this element size. Still, the size of the test element should not be too small. Because for a really small element the influence of the boundary conditions on the stiffness of the elements would be too large. As in the low-frequency region, the stiffness of the elements has a large influence on the amount of sound transmission. If the element is too small the sound reduction is overestimated. Therefore the element dimension was chosen to be 3\*3 m, which is assumed to be an appropriate minimum size for a room separating element. Furthermore, the depth of the rooms was chosen to 4 m. In this way, the room was assumed to be large enough to create a diffuse sound field in the sending room. Especially for the lower frequencies, with a long wavelength, a larger room is needed to create a diffuse sound field. The ISO 12354 states that the room should not be smaller than  $25m^3$ . This requirement is fulfilled.

### MATERIAL PROPERTIES

Some material parameters have a small influence on the amount of sound transmission in the low-frequency range, the results are in Chapter 5. The first parameter is Young's modulus in the x-direction, this parameter showed no significant influence on the sound transmission in the low-frequency range. It is expected that the resonance dip is indeed influenced by this parameter but the resonance dip is above 500 Hz. The second parameter with insignificant influence on the sound transmission is the Poisson coefficient. For the direct sound transmission, the displacement in the direction of the separating element is of influence. Therefore the influence of Poisson's coefficient on the direct sound reduction is expected to be little. The effect of the coefficient on the amount of sound transmission to adjacent elements might be of influence. The last parameter with insignificant influence in the low-frequency range is the density. The model showed results that are in line with the mass law. As in the mass controlled region doubling the mass did result in the additional 6 dB sound reduction.

The two material properties that showed the largest influence on the amount of sound transmission in the low-frequency range are Young's modulus in y and z-direction and the internal loss factor.

The Young's modulus in y and z-direction are of importance for the location of the coincidence controlled region. Since the coincidence region is in the low-frequency range for CLT elements these material properties significantly influence the amount of sound transmission in the low-frequency range. The final values of Young's modulus in the y and z direction are lower than the initially assumed values. The faces of the lamellas of the adjacent layers are glued together but there is no adhesive between adjacent elements within a layer. The gaps between the adjacent elements were up to 3 mm. The stiffness reduction could be due to these small gaps between the elements or knots, as these are not included in the models but might be of influence. Also, the panels are assumed to be fully bonded by the glue. But since the vibrations are small this might be an over-constrained assumption. This could also be a reason for the lower values of Young's moduli.

When the internal loss factor is above 0,03 it is assumed that edge losses are insignificant [56]. The internal loss factor is then assumed to be governing the total amount of damping of an element. The measured internal loss factor for CLT in the low-frequencies is between 0,08 for 50 Hz and 0,04 for 500 Hz. The other losses were assumed to be insignificant and not included in the numerical model. The sensitivity analysis results showed that using a significantly higher internal loss factor of 0,2 or even 0,4 in the numerical models lead to more accurate results. This indicates that other losses than the internal loss, which were not included in the numerical model, are of importance for total the amount of damping. Therefore the assumption that the internal loss factor is governing the total damping does not apply to CLT elements.

A more recent measurement campaign measured the total loss factor of CLT elements instead of the internal loss factor. In the frequency range up to 500 Hz, the total loss factor is between 0,35 for 50 Hz and 0,10 for 500 Hz [18]. The internal loss factor used in the FE models was also in this range. This shows that other losses than the internal loss are significant for the total damping of CLT elements and that the use of the high internal loss factor is correct.

### ADDITIONAL LINING

The models used in Chapter 6 to estimate the effect of additional linings showed results similar to the empirical data. But there is still room for improvement. First, it is important to know the exact material properties of the additional materials. Especially for porous materials and highly elastic materials, the material properties used in a numerical model are of importance. Differences in the material parameters can have a significant influence on the amount of sound transmission. The second point of importance is the effect of the studs. In the second case, there were studs in the measured build-up. Without modelling the studs the model was not able to capture the dip in the sound reduction at the resonance frequency of the mass-air-mass system. This shows the effect of the studs on the dip in the sound reduction. Coupling must be modelled between the CLT element and the additional lining to prevent the lining from moving freely because without the coupling the resonance frequency is estimated incorrectly. The studs were not modelled in this research but already a lot of research has been conducted on this subject. The research showed that the acoustic performance of build-ups with studs can be successfully simulated with FE models [70]. Modelling the studs will increase the computation time of the models as the number of elements increases.



### BOUNDARY CONDITIONS

The results of Chapter 5 show that the boundary conditions of both the direct sound transmission model and the vibration reduction index model significantly influence the amount of sound transmission in the low-frequency range. The boundary conditions affect the natural frequencies and stiffness of the element. This results in differences in the amount of sound transmission. In the numerical model, rigid and free boundaries were investigated. The differences between the results were up to 5 dB per frequency, which is significant. In reality, the boundary conditions will be neither free nor rigid but somewhere in-between. Changing the boundary condition to semi-rigid would improve the results. For example, the location of the dip around 315 Hz in the measurement results of the three different 175 mm 5-ply elements is predicted to be around 250 Hz by the numerical model, see figure 5.3 6.2. The rigid boundary conditions are an resulting in a stiffer element and for a stiffer element, the resonance dips are in lower frequencies.

### MESH

During the research models with a mesh size of 0,2 m instead of 0,15 m were used in the beginning. Models with a mesh size of 0,2 m only take 5 minutes to run instead of the 30 minutes needed for a model with a mesh size of 0,15 m. The accuracy was much lower but in this way, the overall trend could be predicted quickly. This shows the large influence of the mesh size on the amount of computational time. A larger mesh size gives inaccurate results in the higher frequencies. To be able to use the numerical model in the highest frequencies of interest for building acoustics (3150, 4000 and 5000 Hz) the mesh size should be smaller than 0,017 m. The increase in computational time when the mesh size was decreased from 0,2 to 0,15 m indicates that the computational time for a model with a mesh size of 0,017 m would increase drastically. Therefore it is assumed that the numerical models are not suitable for the prediction of the sound transmission in the higher frequencies as the computational times would become higher than preferred especially in the design stage of a project.

### SOUND SOURCE

To create the diffuse sound field in the sending room a mass sound source of  $1\text{ kg/m}^2$  was used. In figure 6.1, it can be seen that the sound source indeed did create a diffuse sound field. To determine the sound reduction through an element, it is important to create a sound level in the sending room that is loud enough to be picked up in the receiver room. The sound level in the sending room was over 150 dB and created a sufficient sound level in the receiver room. Therefore the use of this mass sound source is assumed to be a good modelling technique for the modelling of a sound source in the Ansys model.

## 7.2. VIBRATION REDUCTION INDEX MODEL

The level of accuracy of the vibration reduction index model was harder to quantify since the individual connectors which were present in the measurement were not included in the model. But the overall trend showed to be in agreement with the measurements.

### GEOMETRY

The geometry of the model is similar to the geometry of the measurement setup. The same dimensions were used for the CLT panels. Small patches (face elements) were attached to the outer CLT lamella. In this way, the measurement eyelets and the head of the shaker are mimicked. It was assumed that these small elements did not influence the results as they are small compared to the CLT elements.

### MATERIAL PROPERTIES

The sensitivity of the model to the material properties was tested on the direct sound transmission model. The fitted values that came out of this analysis were used for the material properties of the elements in the vibration reduction index model. It was assumed that these values are appropriate for both models since the same CLT elements were modelled.

The material properties of the elastic interlayers are based upon data provided by the manufacturer and are therefore also assumed to be appropriate to use. The use of highly elastic materials like the materials used as elastic interlayers are more complicated to model. Ansys suggests that it is needed to determine the coefficients of the equation used for stress-strain curve generation and to characterize the material correctly. These material properties were not defined for the elastic layers in the model. This could be the reason that the difference between the effect of different interlayers was limited. To better predict the effect of a specific



interlayer it could be beneficial to take the time to predict the stress-strain curve and the correct material characteristics.

#### BOUNDARY CONDITIONS

In the vibration reduction index model in Chapter 6, the difference between the model with hold-down on the edges of the junction and the fully free model also showed significant differences with some outliers up to 15 dB. The ISO standard 104848 prescribes the use of fully free models.

The boundary conditions showed to have a significant influence on both the amount of direct sound transmission and the vibration reduction index. The significant differences due to different boundary conditions are important to keep in mind when using measured data. If the boundary conditions in the test facility are different from the boundary conditions on-site the measured data could give an inaccurate estimation.

#### MESH

The mesh was assumed to be 0,15 m, similar to the mesh size of the direct sound model. This size is based on the highest frequency of interest and the speed of sound in the air. In this model, the sound waves only travel through CLT and not air. The speed of sound in CLT is higher than the speed of sound in the air. Therefore a larger mesh size could be used to still get accurate results. A larger mesh size would also be beneficial for the reduction of computation time.

When the bolts are modelled also bolt holes are needed in the CLT panels. The mesh around bolt holes is fine, resulting in a large number of nodes. The mesh is fine because the bolt holes have small dimensions. Without modelling the bolt holes the mesh size can be larger which reduces the computational time.

#### LOAD VECTOR

The load vector is applied on a small patch and is therefore not a point load but an equally distributed force over the small patch. This was done to prevent the model from really high peak forces. The largest deformation of the model, as shown in figure 6.5, occur at the location of the load application but the deformation is small, in the order of  $3,5 * 10^{-8} mm$ . This is a really small deformation and therefore the use of the small patch is assumed to be similar to the use of the shaker and peak forces are prevented.

#### ELASTIC INTERLAYER

The effect of the elastic interlayer, as shown in Chapter 5, is limited in the low-frequency range, which the measured data already showed in Chapter 3. The numerical models also showed small differences of a junction with and without interlayers. The differences are within a range of 3 dB. The variance of the measured junctions without interlayer is larger than the variance of the junction with an interlayer. This indicated that the application of an elastic interlayer reduces the influence of the number and type of connectors becomes smaller. The differences between the estimation of the vibration reduction index by the ISO 12354 and the measurements are large. The differences are up to 15 dB, where the code overestimates the vibration reduction. As the overestimation of the vibration reduction index leads to an underestimation of the amount of flanking sound transmission the indices prescribed by the standard should be used with care. The estimation of the numerical models is more in range with the measurement results. This shows that the numerical models are capable of estimating the vibration reduction index of a junction with an interlayer. The absence of the connectors in the model is assumed to be of less significance than for a bare junction as the interlayer reduces the influence of these connectors.

#### CONNECTORS

The empirical data shows that type and number of joints applied in a CLT joint can considerably affect the level of sound transmission. The effect is visible over the entire frequency spectrum of 100-3150 Hz. To be able to more accurately estimate the effect of the connectors being used in constructions, it is essential to consider the type and number of joints that are used in a CLT joint. An attempt was made to include these components in the numerical models to better estimate the effect of the connectors used. Different methods for modelling the connectors have been studied: solid elements, beam elements or line bodies. The methods are explained in more detail in appendix E.

The use of solid elements, beam elements or line bodies as connectors between the elements all resulted in large models. Ansys states that for these types of models a PC with minimal 16 GB RAM is required. Due to the limited memory and RAM of the available PC, it was not possible to run these models. It is expected that

a PC with 16 GB RAM and more available memory is capable of running these models. This could give more insight into the level of detail needed to capture the effect of the connectors on the vibration reduction index.

Due to a large number of additional loads when modelling the connectors with any of the three mentioned modelling methods the used PC was unable to run the models. Therefore only the connection between the panel faces was considered in the final vibration reduction models. Here the interface between the panels is a frictionally bonded connection. By using only a frictionally bonded connection between the panels the effect of connectors cannot be captured. But since the results still show a better match with the measurement results than the ISO standard, the numerical model still seems an appropriate tool.

### 7.3. LOW-FREQUENCY SOUND TRANSMISSION

In this research, the focus is on the low-frequency sound transmission as literature claimed that this frequency range is the main reason for annoyance [43] [52]. Still, the frequencies below 100 Hz are not included in the Dutch building code. But since the material CLT is mainly used for high-end apartment buildings the expectation of residents are high when it comes to acoustic comfort. Build-ups that meet the building requirements do not meet these high expectations levels. To predict the direct sound transmission research showed that including the frequencies as low as 50 Hz would lead to more accurate results of the total direct sound transmission. The direct sound models were therefore calculated from 50-200 Hz. The building code of Sweden already included the frequencies 50, 63 and 80 Hz [17]. They hereby acknowledge the importance of low-frequency sound transmission in lightweight buildings. As the first-panel resonance frequency and the coincidence region are both in the frequencies below 100 Hz these frequencies should not be excluded when designing a CLT building. The results presented in chapters 5 and 6 of this research show that low-frequency sounds can be estimated with FE element models, as the results are in line with measurement results.

The direct sound transmission is measured up to 50 Hz, lower frequencies become hard to measure because of the long wavelength. The numerical model is also able to predict the sound transmission in frequencies below 50 Hz. Therefore these results could not be verified by the measurement data. Since the models predict the trend of the sound transmission within the range of 3 dB in the frequency range 50-500 Hz it is assumed that the results below 50 Hz are also accurate. Especially since the results in the lower range are most in line with the measurements, the largest differences are all above 315 Hz. Also, research that used a similar numerical model to predict the sound transmission through a wall with a window compared the results to measurement results from 10-100 Hz. The results showed close agreement with the measurement data for all studied frequencies also below 50 Hz [71].

To predict the impact sound transmission research showed that including the frequencies as low as 20 Hz would lead to more accurate results of the total impact sound transmission. The numerical vibration reduction index model was therefore calculated from 20-500 Hz. The measured data for the vibration reduction index was only available for frequencies above 100 Hz. The results of the numerical model and the measured data are in the same range from 100-500 Hz. Below 100 Hz the vibration reduction index is increasing, this trend is not verified by measured data. But as the accuracy of the model should increase when the frequency of interest decreases it is assumed that the results below 100 Hz are reasonably accurate.

### 7.4. REDUCE NUMERICAL MODEL SIZES

The numerical models predict the direct sound transmission of simple build-ups within a range of 3 dB. The computational time for a bare 5-ply CLT element is around 30 minutes. For build-ups with additional lining but without battens or studs, the computational time increases to 40 minutes. The specifications of the used PC are stated in Appendix E. This is assumed to be an average PC that is available for acoustical advisors. This means that on an average PC simple build-ups can be estimated accurately within reasonable times in the design stage of a project. To be able to quantify the effect of the battens or studs on the resonance frequency dip, these elements must be incorporated in the numerical models, which increase the computational time drastically. The battens and studs are small elements which therefore require a small mesh. This leads to a large additional amount of nodes. In the final design, it is important to know the exact location of the dips in the sound insulation to be able to reduce these dips to acceptable levels. By modelling the studs and battens the mass air mass dip can probably be predicted but this will come with an increased computational time. This increased computational time is unwanted in the design stage but can be higher for the final design.

If the numerical models will be used in the design phase of a project it is of importance to be able to quickly estimate several design options. The direct sound transmission model is quick and able to estimate the direct sound transmission within 30 minutes. The vibration reduction index model takes longer (up to 1 hour) and must be run multiple times for the different excitation points. As each panel has 3 excitation points the total run time is up to 9 hours. Therefore a reduction of the model sizes of the vibration reduction index model would be beneficial. A recent study into numerical modelling of cross-laminated elements showed that the use of shell elements instead of solid elements showed computational efficiency. The runtime and required RAM were reduced whilst the accuracy remained high. The runtime improved by a factor of two and the required RAM was reduced by a factor of 12 [72].

# 8

## CONCLUSION

This research aims to answer the following question: *'How can the effect of sound-reducing measures on the direct and flanking sound transmission between two rooms in a cross-laminated timber apartment building be modelled in order to estimate the total sound transmission?'* The results and observations of this research are used to answer this question.

This research has implicitly demonstrated the flexibility and accuracy of numerical sound transmission models. The models estimate the direct sound and vibration reduction index within an acceptable range with the measured data than the ISO standard and are verified for different cases. The direct sound transmission model can determine the sound transmission within a range of 3 dB where ISO standards show differences up to 5 dB per frequency. The vibration reduction index model with frictionally bonded contact region between the panels calculated the vibration reduction index in the same range as the measured results. In the low-frequencies, the ISO standard overestimates the vibration reduction index for all the measured connections. For both the direct sound transmission model and the vibration reduction index model, the results show a great resemblance with measured data. The numerical models give a better approximation of the sound transmission than the ISO standard. Therefore it can be concluded that computational sound transmission models can serve as a base for the estimation of the direct and flanking sound transmissions. The models can increase the accuracy of the estimation of the sound transmission in the design stage of a project.

However, when FE models are used to estimate sound transmission there are some uncertainties. This starts by defining the material properties. Especially the damping must be determined beforehand for the CLT elements. The individual lamellas of the CLT elements must be modelled in order to capture the coincidence effect. In addition, the boundary conditions have a major impact and require accurate definition in advance. Once these parameters are determined, the direct sound transmission can be accurately estimated in the low frequencies. For the modelling of the vibration reduction index, the boundary conditions also showed significant influence. So also for this model, the boundary conditions require accurate definition. The effect of the elastic interlayer is limited in the low frequencies on the vibration reduction index but can be captured with the model. The effect of the connectors was not determined, but friction contact regions showed great similarities with the measured data of various types of connections.

In conclusion, the numerical models demonstrated in this research showed to be able to capture the sound reduction in the low-frequency range (up to 500 Hz) within the acceptable range of 3 dB. Because of the overestimation of the amount of sound reduction by the ISO 12354, it is necessary to collect measured data of a similar concept to estimate the sound reduction in the design stage. This research contributes to better-substantiated sound reduction estimations in the design stage of a project if measurements of similar build-ups are not present.



### 8.1. RECOMMENDATIONS FOR THE USE OF THE ISO 12354

The ISO 12354 is not correctly adapted to the material CLT. The direct sound transmission is captured within the range of 4 dB but with outliers of 7 dB. This means that for some frequencies the amount of sound transmission is significantly over or underestimated. The overall trend of the direct sound is similar to the measured results. So in the early design stage, the code can be used to estimate the amount of direct sound transmission. But to comply with the differences between the standard and the measurements a small reduction could be applied to the results. Also, the statement that for material with an internal loss factor higher than 0,03 other losses become insignificant is proven to be wrong by this research.

The effect of additional lining is very roughly calculated by the standard and it is not possible to determine the effect of more than one layer. Which results in large differences between the calculated values and the measured results. Therefore it is suggested to use measurement data of similar build-ups instead of the results of the standard.

The vibration reduction index is largely overestimated by the standard. When using this vibration reduction index when determining the amount of flanking sound transmission the amount of flanking is significantly underestimated. The differences between the measured results and the results of the code are up to 15 dB. Using the calculation method for the vibration reduction index will result in major underestimations and can lead to finalized projects that do not meet the acoustic requirements. The formulas used to calculate the indices should be revised.

The standard does not include a calculation method to estimate the effect of an elastic interlayer on the vibration reduction index. The effect of the elastic interlayer is limited in the low-frequency range. But the standard could include formulas to calculate the vibration reduction index of junctions with interlayers.

The connections between elements in traditional buildings are line connections. In CLT constructions the elements are connected by several connectors. Therefore the standard does not include the effect of the connectors. Even though the connectors significantly influence the vibration reduction index also in the low-frequency range.

### 8.2. RECOMMENDATIONS FOR THE USE OF FE MODELS

To accurately estimate the sound transmission through a CLT panel the individual lamellas must be modelled. The grain direction of the individual lamellas can be alternating and the individual lamellas can be assumed to be bonded. For elements with a higher number of layers, it is more important to model the individual layers. The most influential material properties of the CLT on the amount of sound transmission in the low-frequency range are Young's modulus in y and z-direction and the internal loss factor. The Young's modulus in the y and z-direction are of influence of the location of the coincidence dips. The material properties need to be defined in advance, especially the damping and Young's moduli.

The effect of additional linings of simple build-ups can be captured within the range of 5 dB. It is important to know the exact material properties of the additional linings to give an appropriate approximation of the sound reduction. The sound reduction of build-ups with studs or porous materials are more complex and needs additional research. The effect of the studs or battens on the amount of sound transmission can be significant and therefore should be included in the model.

The effect of an interlayer and the connectors can be estimated by modelling these elements in the model. The effect of an elastic interlayer is not significant in the low-frequency range. The differences are within a range of 5 dB compared to the same junction without an interlayer. The effect of an interlayer and the connectors can be estimated by modelling these elements in the model.

The numerical models were not capable of capturing the effect of the connectors. The amount of detail required was too large for the available computational capacity. A frictionally bonded connection between the panels resulted in vibration reduction indices that are in the range of the measurement results of panels that are connected with several screws and angle brackets.

### 8.3. FURTHER RESEARCH

In this research, the airborne sound transmission was modelled in the direct sound transmission model. The same method could be extended for the contact sounds. The direct airborne sound model needs a few adjustments. The first adjustment is the sound source, which must be changed from an airborne sound to an impact sound. The second adjustment is the post-processing step. The formulas for the calculation of the impact sound reduction are different from the airborne sound transmission formulas. The vibration reduction index model is also relevant for the impact sound transmission and does not need adjusting.

During this investigation, individual parts of the model were verified, namely the direct sound transmission model and the vibration reduction index model but not the full-size model. In the future, the numerical results must be verified with measurement results of realized CLT apartments buildings.

The computational capacity of the computer created a bottleneck in this research. Possible model reductions can be investigated. In this model solid elements were used, the use of face elements could reduce the model size significantly. Another option would be to use scaled numerical models. Important is to scale the wavelengths in the airborne and in the structure-borne sound fields in the same way. With a scaling factor, the computational costs could be reduced drastically. The accuracy of scaled models or models with face elements needs investigation.

Additional research is needed in order to be able to create numerical models which are able to capture the effect of the connectors. Different modelling techniques were incorporated in this research but without the desired outcome. Research into smaller-scale models or other types of connection modelling could provide more data about the effect of different connectors.

The rooms modelled were rectangular and the layout of the two adjoining rooms was identical. The use of numerical models makes it possible to capture the sound transmission between rooms that are not perfectly aligned. The effect of different alignments between rooms could be investigated in the future.

Additional linings are often connected to the load-bearing element with bats of studs. Additional research is needed on how these elements must be incorporated in the numerical models. The inclusion of these elements could lead to more accurate results. Porous materials are also commonly used as sound-reducing materials. The modelling of these materials needs more attention than the modelling of solid material to better capture the sound reduction.





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# A

## CASE STUDY HAUT



Figure A.1: Impression of the HAUT building [27]



HAUT is a 21 story high residential building in Amsterdam. The construction started in 2019 and the building is almost finished. The building is 73 meters high and therefore the highest timber building in the Netherlands. When finished the building will be the first residential building in the Netherlands with the classification 'BREEAM-outstanding'. The aim was to use timber elements where possible [27].

The structural design consists of internal load-bearing walls, which also function as separation walls between residences. The floors are timber concrete composite floors. The floors are supported on top of the CLT load-bearing walls. Creating a platform construction. The two layers of the basement are made with concrete to create a robust base for the timber tower. The lateral stability of the building is guaranteed by a concrete core and two CLT shear walls, the stability system is shown in figure A.2. Around the perimeter of the floors, there is a tie beam. This tie beam ensures the diaphragm action between the floor elements. In this way an acoustic separation could be applied between the floors of different residents [27].

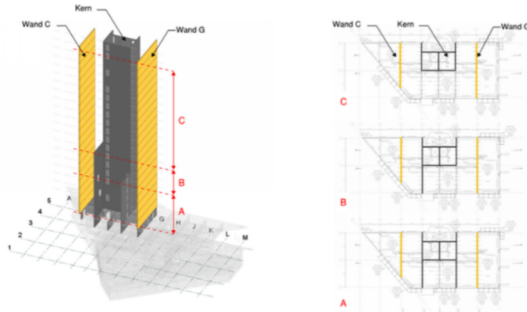


Figure A.2: Stability system for HAUT with a concrete core and two CLT shear walls [27]

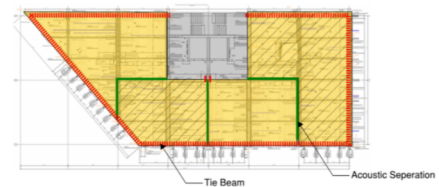


Figure A.3: Principle of the diaphragm [27]

The floor system was a critical point for the project. The floor influenced the stability system and had to meet all the building physics criteria. The floor consists of a 160 mm CLT element with 80 mm concrete on top. The additional mass was needed for the acoustical requirements. At the end of the floor element, the concrete layer fills the full height. In this way, it was possible to use the platform technique without the problem of the low strength of the timber floor elements perpendicular to the grain [27]. Other sound-reducing measures are the use of decoupled sound insulation panels in front of the CLT walls and the decoupled floor elements between different residences. The junction is shown in figure A.4.

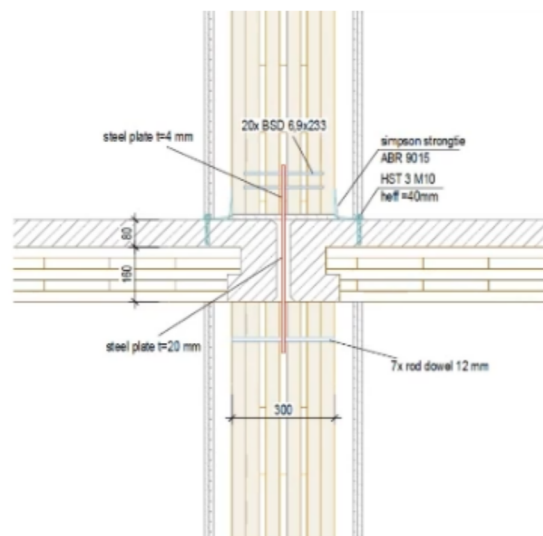


Figure A.4: Detail of the junction in HAUT [28]

Arup was involved in structural engineering, fire safety, sustainability, building services, and building physics. A meeting with the acoustical advisor of the HAUT project gave more insight into the design process of the CLT buildings and the acoustical attention points. The main learning points are given here.

- It is important for an acoustical advisor to work closely with the structural engineer. From the structural point of view, a lot is possible when you are involved early on. Therefore in timber projects, it is important to involve the structural engineers and building physics consultants in the early stages. Structural engineers should know the limitations. The largest limitations are different for different projects. The main challenge is controlling the flanking noise transmission which conflicts with the overall stiffness of the building, for example, the diaphragm working of the floor is affected when decoupling is required for the acoustics.
- Acoustic consultant should consider striving for a higher level of sound insulation than required in the Bouwbesluit. Especially since CLT residential buildings are now usually high-end apartments it is worth considering to aim for higher values than stated in the Bouwbesluit. It is not directly needed to change the building code, but additional requirements are needed for the low-frequency sounds. Any lightweight building requires extra attention for low-frequency sound isolation, but this is not in Bouwbesluit. This makes it harder to convince a client to take additional measures since it is not required by the code. What could help is to let the client or the resident experience/hear the difference instead of just showing the numbers.
- Flanking sound reduction is important. Horizontal flanking is in the end governing. The direct sound transmission can be easily reduced with additional linings. Which leaves the flanking transmission through the junctions as one of the limiting factors.
- The sound-reducing measures depend on the projects, in apartment buildings the room separating elements is the optimal location for decoupling. This can lead to a rearrangement of the apartment dividing walls and the apartment layouts. So here the right balance must be found on where to use decoupling and where to have things connected. Layouts with shifted apartments result in more points where decoupling is needed. This influences the overall stiffness of the building. During the design phase, it goes back and forth on what is feasible and what is not feasible.
- A hybrid solution reduces the floor thickness significantly while still meeting the requirements for human-induced vibrations. Also, the additional mass positively influences the amount of sound reduction. The choice for a hybrid floor in the HAUT project was mainly governed by the preferences of the CLT producer. For other projects, a hybrid solution is not always the best solution.
- Fully CLT junctions are possible for residential buildings but, an additional mass layer is required. An easy option is to add a concrete layer because it is already tested for acoustics and fire. The HAUT floor build-up was tested in a lab. For projects, a full-scale mock-up test can be useful for the junction.
- When redesigning a concrete building to a timber building it will become a completely different building. Know the do's and don'ts for CLT since it is a different material than concrete. It will affect your square meters of apartments, ventilation positions, electrical points and locations of the plumbing. The main differences are the apartment layouts. In CLT you have more limitations for the layout, it is not possible to create a recess everywhere for example for a plumber. It is not so easy to swap the location of the bedroom and bathroom for example or change the location of the kitchen.
- It is not possible to show several planes of bare CLT but from the fire safety perspective. Especially for residential as the use of sprinklers is not common. For offices, this has less of an impact to introduce sprinklers so there are more options. From an acoustical point of view, there are more possibilities for showing the CLT. So the problem is governed by fire.
- Several producers have measured several build-ups but usually, these build-ups are not exactly the same as the design. CLT producers have a particular way of building, so for every different producer, the design can change a lot.
- SEA or FEA models can be used for detailed calculations but are usually very expensive, something the budgets generally do not allow.



- The 'optimal' solution for every timber building is different. Different design goals, building configurations, material stocks and the contractors' preferences are just a few examples of what can influence the design. There is no one size fits all solution in the building industry.

# B

## CALCULATION STRENGTH CONNECTION

### B.1. FAILURE MODES

Connections can fail in different types of ways. The failure modes used in the Eurocode 5 are the Johnson failure modes. A difference is made between fasteners in single or double shear and between timber to timber or timber to steel connections. The lowest value is the governing failure mode.

#### B.1.1. TIMBER-TIMBER CONNECTIONS

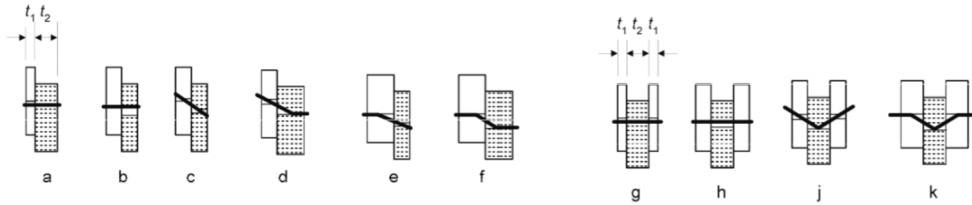


Figure B.1: Failure mechanisms timber-timber

Single shear:

$$F_{v,rk} = \begin{cases} f_{h,1,k} * t_1 * d & (a) \\ f_{h,2,k} * t_2 * d & (b) \\ 1,05 * \frac{f_{h,1,k} * t_1 * d}{2+\beta} * [\sqrt{\beta + 2 * \beta^2 * [1 + \frac{t_2}{t_1} + \frac{t_2^2}{t_1^2}]} + \beta^3 * \frac{t_2^2}{t_1} - \beta * (1 + \frac{t_2}{t_1})] + \frac{F_{ax,rk}}{4} & (c) \\ 1,05 * \frac{f_{h,1,k} * t_1 * d}{2+\beta} * [\sqrt{2\beta * (1+\beta) * \frac{4\beta * (2+\beta) * M_{y,rk}}{f_{h,1,k} * d * t_1^2}} - \beta] + \frac{F_{ax,rk}}{4} & (d) \\ 1,05 * \frac{f_{h,1,k} * t_2 * d}{2+\beta} * [\sqrt{2\beta^2 * (1+\beta) * \frac{4\beta * (1+2\beta) * M_{y,rk}}{f_{h,1,k} * d * t_2^2}} - \beta] + \frac{F_{ax,rk}}{4} & (e) \\ 1,15 * \sqrt{\frac{2\beta}{1+\beta}} * \sqrt{2M_{y,rk} * f_{h,1,k} * d} + \frac{F_{ax,rk}}{4} & (f) \end{cases} \quad (B.1)$$

Double shear:

$$F_{v,rk} = \begin{cases} f_{h,1,k} * t_1 * d & (g) \\ 0,5 f_{h,2,k} * t_2 * d & (h) \\ 1,05 * \frac{f_{h,1,k} * t_1 * d}{2+\beta} * [\sqrt{2\beta * (1+\beta) * \frac{4\beta * (2+\beta) * M_{y,rk}}{f_{h,1,k} * t_1^2}} - \beta] + \frac{F_{ax,rk}}{4} & (j) \\ 1,15 * \sqrt{\frac{2\beta}{1+\beta}} * \sqrt{2M_{y,rk} * f_{h,1,k} * d} + \frac{F_{ax,rk}}{4} & (k) \end{cases} \quad (B.2)$$

### B.1.2. STEEL-TIMBER CONNECTIONS

For steel-timber connections the failure mechanisms are different. Here the failure mechanisms for the timber and steel elements need to be verified. There are different formulas for thin and thick steel plates. A plate is classified as thin if the thickness is equal to or smaller than  $0,5*d$ .

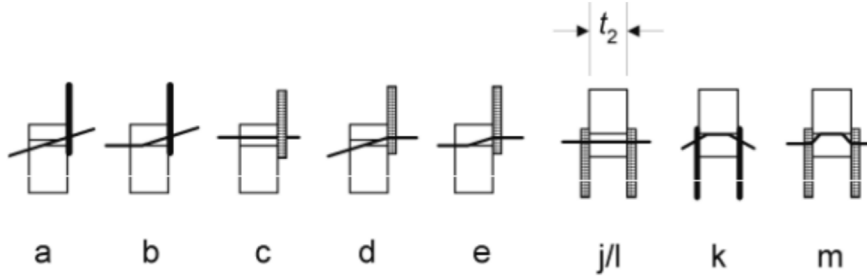


Figure B.2: Failure mechanisms timber-steel

Single shear (thin plate):

$$F_{v,rk} = \begin{cases} 0,4 * f_{h,k} * t_1 * d & (a) \\ 1,15 * \sqrt{2M_{y,rk} * f_{h,k} * d + \frac{F_{ax,rk}}{4}} & (b) \end{cases} \quad (B.3)$$

Single shear (thick plate):

$$F_{v,rk} = \begin{cases} f_{h,k} * t_1 * d & (c) \\ f_{h,k} * t_1 * d * [\sqrt{2 + \frac{4M_{y,rk}}{f_{h,k} * d * t_1^2}} - 1] + \frac{F_{ax,rk}}{4} & (d) \\ 2,3 * \sqrt{2M_{y,rk} * f_{h,k} * d + \frac{F_{ax,rk}}{4}} & (e) \end{cases} \quad (B.4)$$

Double shear (thin plate):

$$F_{v,rk} = \begin{cases} 0,5 * f_{h,2,k} * t_2 * d & (j) \\ 1,15 * \sqrt{2M_{y,rk} * f_{h,2,k} * d + \frac{F_{ax,rk}}{4}} & (k) \end{cases} \quad (B.5)$$

Double shear (thick plate):

$$F_{v,rk} = \begin{cases} 0,5 * f_{h,2,k} * t_2 * d & (l) \\ 2,3 * \sqrt{2M_{y,rk} * f_{h,2,k} * d + \frac{F_{ax,rk}}{4}} & (m) \end{cases} \quad (B.6)$$

### B.1.3. ROPE EFFECT

The factor  $\frac{F_{ax,rk}}{4}$  represents the rope effect. The maximal value of the rope effect depends on the type of fastener. The maximal value is presented as a percentage of the Johnson part.

Fastener	Maximal value rope effect
Round nails	15%
Screws	100%
Bolts	25%
Dowels	0%

Table B.1: Rope effect

A connection subjected to axial and shear forces must satisfy the following equation:

$$\frac{F_{ax,ed}^2}{F_{ax,rd}} + \frac{F_{v,ed}^2}{F_{v,rd}} \leq 1 \quad (\text{B.7})$$

#### **B.1.4. YIELD MOMENT**

The yield moment is the value for the moment that would result in a plastic hinge in the connection. The yield moment is dependent on the tensile strength of the material of the fastener and the diameter of the fastener. The characteristic yield moment according to the Eurocode 5 for round bolts and dowel can be calculated by using the following formula:

$$M_{y,rk} = 0,3 * f_{u,k} * d^{2,6} \quad (\text{B.8})$$



# C

## ABSORPTION COEFFICIENTS

In this appendix, the absorption coefficients of different materials are given. These coefficients are used in the numerical models on the interface between the air of the room and the surface of the room separating elements. The absorption coefficient is frequency-dependent. A low absorption value results in more sound reflection back into the room.

Frequency [Hz]	CLT	Mortar	Gypsum
0	0,150	0,011	0,400
50	0,145	0,012	0,360
63	0,144	0,012	0,340
80	0,140	0,012	0,320
100	0,140	0,012	0,290
125	0,140	0,013	0,280
160	0,130	0,013	0,260
200	0,128	0,014	0,230
250	0,120	0,015	0,100
315	0,110	0,016	0,090
400	0,090	0,018	0,070
500	0,080	0,023	0,050
630	0,080	0,023	0,048

Table C.1: Frequency dependant boundary absorption coefficients [20]





# D

## MODELING THE LAMELLAS OF THE CLT

Two different methods are investigated for the modelling of the CLT panels. The first method is to model the elements as one solid element. The second method is to model the CLT lamellas as individual elements. Here the results of a solid element and a layered element are compared to the experimental results for a 3, 5, 7 and 9 ply element. The results are shown in figure D.1 to D.4. The used material properties are given in table D.1.

Type of modeling	Layers	Solid 3-ply	Solid 5-ply	Solid 7-ply	Solid 9-ply
$\rho$ [ $kg/m^3$ ]	500	500	500	500	500
Ex [MPa]	11000	7433	6720	6414	6244
Ey [MPa]	300	3867	4580	4886	5056
Ez [MPa]	300	3867	4580	4886	5056
vxy [-]	0,3	0,3	0,3	0,3	0,3
vyz [-]	0,4	0,4	0,4	0,4	0,4
vxz [-]	0,3	0,3	0,3	0,3	0,3
Gxy [MPa]	650	650	650	650	650
Gyz [MPa]	65	65	65	65	65
Gxz [MPa]	650	650	650	650	650
$\eta$ [-]	0,08	0,08	0,08	0,08	0,08

Table D.1: CLT element material properties used in FEM for the solid element and layered element [38]

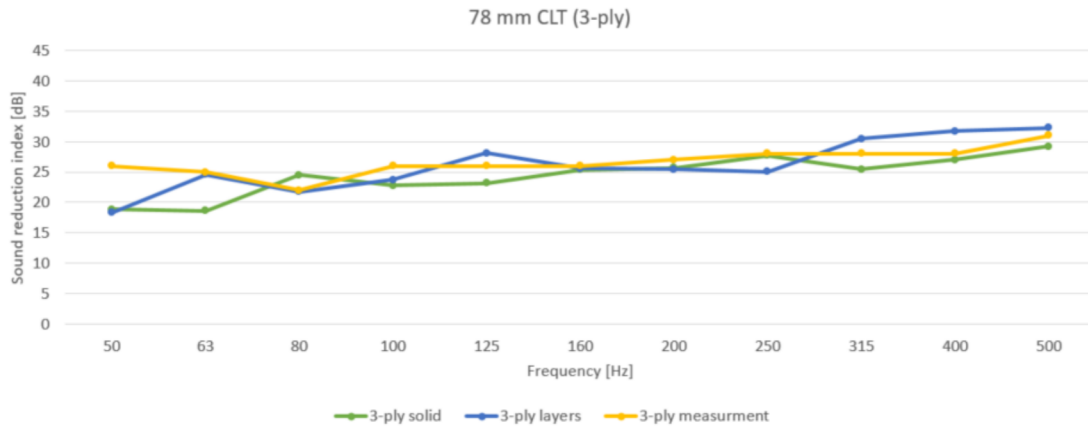


Figure D.1: Results of the sound reduction index of a solid CLT element and a layered 3-ply CLT element compared to experimental data

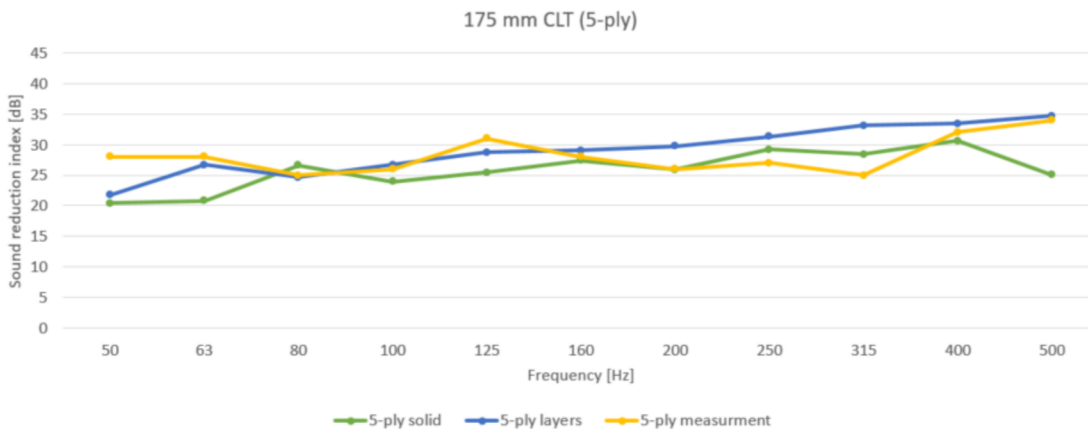


Figure D.2: Results of the sound reduction index of a solid CLT element and a layered 5-ply CLT element compared to experimental data

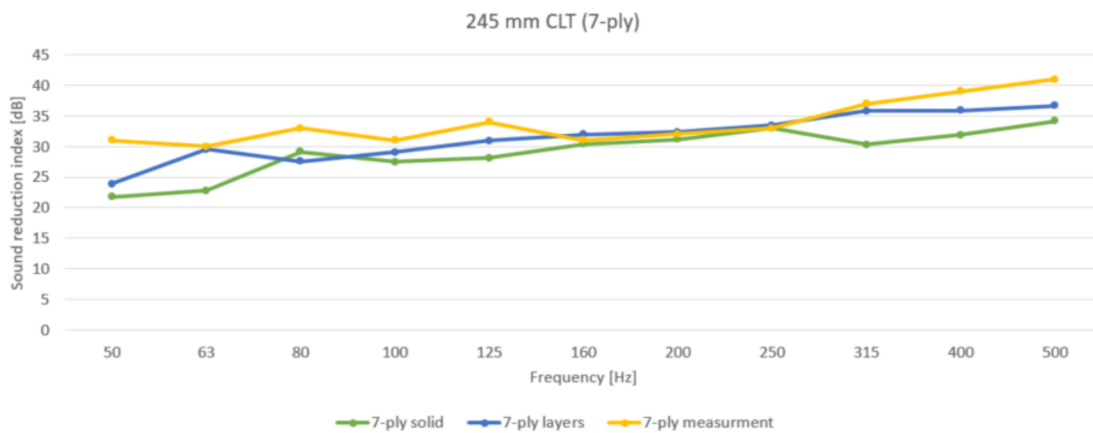


Figure D.3: Results of the sound reduction index of a solid CLT element and a layered 7-ply CLT element compared to experimental data

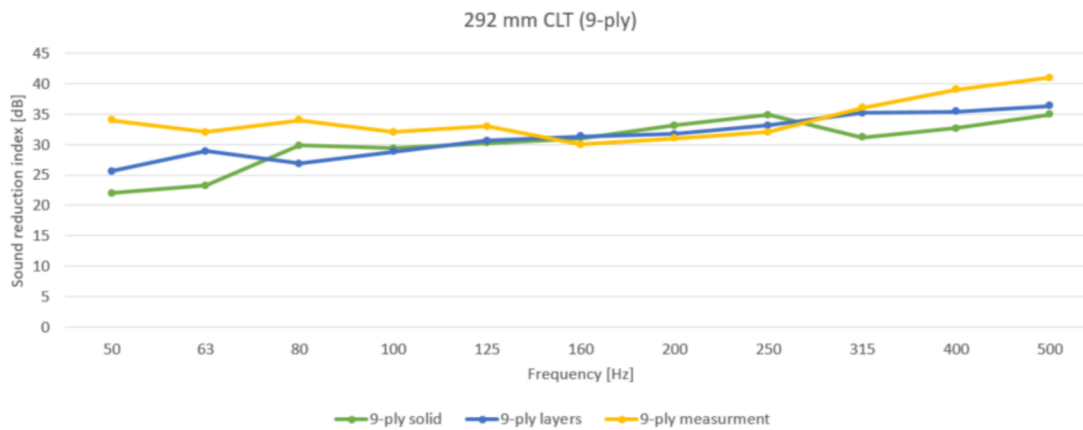


Figure D.4: Results of the sound reduction index of a solid CLT element and a layered 9-ply CLT element compared to experimental data

The average absolute difference for the frequencies 50-500 Hz and the maximal difference with measurements are given in table D.2. The absolute average difference between the layered models and the measurement results are smaller than the differences between the solid models and the measurement results. Also, the maximal absolute difference is equal to or smaller for the layered element. Therefore it is concluded that the layered models generate more accurate results. The higher the number of layers in the CLT element the lower the accuracy of the numerical model. The difference between the layered model and the solid model also increases with the number of layers.

	3-ply		5-ply		7-ply		9-ply	
	Solid	Layers	Solid	Layers	Solid	Layers	Solid	Layers
Average absolute difference [dB]	3	2	4	3	5	3	5	3
Maximal absolute difference [dB]	7	7	9	8	9	7	12	8

Table D.2: Comparison between the differences with measurements for solid elements or layered elements for a different number of layers



# E

## MODELLING THE BOLTED CONNECTIONS

According to the measurements results of Rothoblaas the type, size, and amount of bolts influences the vibration reduction index. Different FEM modelling approaches were used to model the bolted connections between the CLT panels. They have been compared based on the amount of pre-processing, computational time and modelling accuracy here. The different methods which were investigated are modelling the screws as solid elements, modelling the screws as beam elements, modelling line bodies as screws and modelling only the frictional surface between the elements. The PC device specifications used to run the vibration reduction index models are given in below.

Processor (CPU)	Intel(R) Xeon(R) CPU E3-1280 V2 @3.60 GHz 3.60 GHz
Operating system	Window 10 Enterprise 64-bit operating system, x64-based processor
Memory	8.00 GB RAM
Storage	500 GB internal storage drive

### E.1. SOLID SCREWS

For this method, the screws are modelled as solid elements. These elements are bonded to the panels. From the investigated methods this one needs the most per processing as every single bolt needs to be created in the geometry environment. The holes of the bolts need to be created first and then the solid elements are created inside the bolt holes. The total computational time is unknown as the PC used was unable to calculate these models. The accuracy of this method was expected to be the most accurate since the vibrations in the bolts would be calculated as well as the amount of vibrations transmitted.

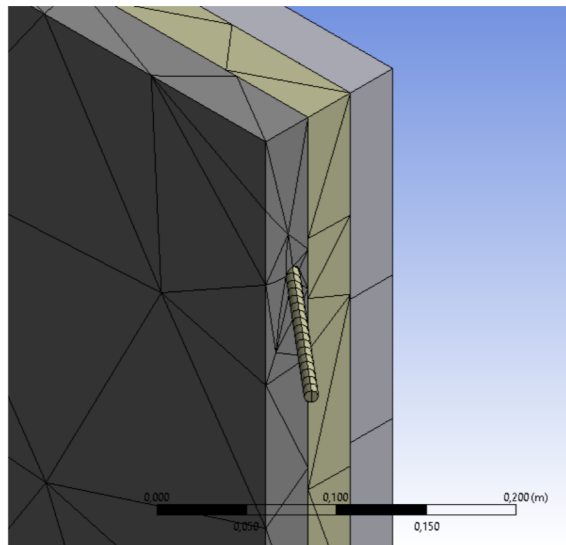


Figure E.1: Visualization of the model with solid elements as bolts in one of the CLT panels

## E.2. BEAM ELEMENTS

This method is slightly different from the first as the screws are not modelled as solid elements but as beam elements. These elements are connected at the faces of the bolt hole to the faces of the beam element. This method also needs quite some pre-processing as for every single bolt a beam element must be created. The holes of the bolts need to be created in the geometry environment and the beam element are generated after. The total computational time is also unknown as the PC used was unable to calculate these models. The amount of elements is lower than for the solid bolts as the beam elements do not require a mesh. Therefore the total computational time is expected to be less than for the model with the solid element screws. The accuracy of this method was expected to be quite accurate since the beam elements would transfer the vibrations from one panel to the other. But the stresses in the bolts themselves would be unknown.

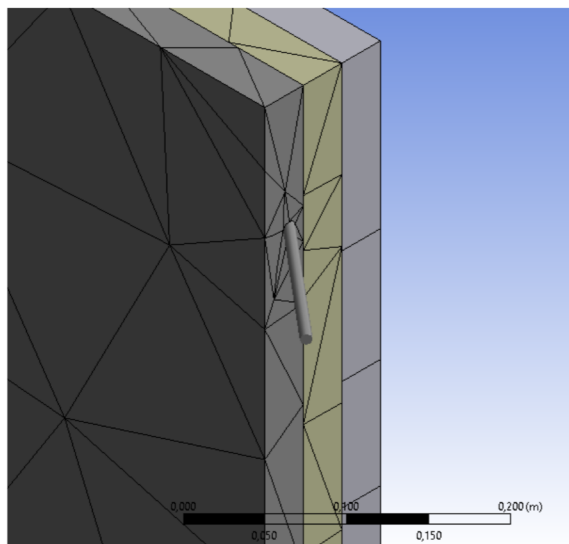


Figure E.2: Visualization of the model with beam elements as bolts in one of the CLT panels

## E.3. LINE BODY

The next method is the most simplistic. Here the bolt joint is simplified and modelled as a line body. For this method, the pre-processing contains the creation of the bolt holes after which the line bodies can be



generated at once, both in the geometry environment. The total computational time is also unknown as the PC used was unable to calculate these models. The amount of elements is lower than for the beam elements bolts. The accuracy of this method was expected to be less than for the method with the beam elements. Because the line elements only connect the ends of the line to the outside of the CLT panels. This method also does not provide the stresses in the bolts themselves.

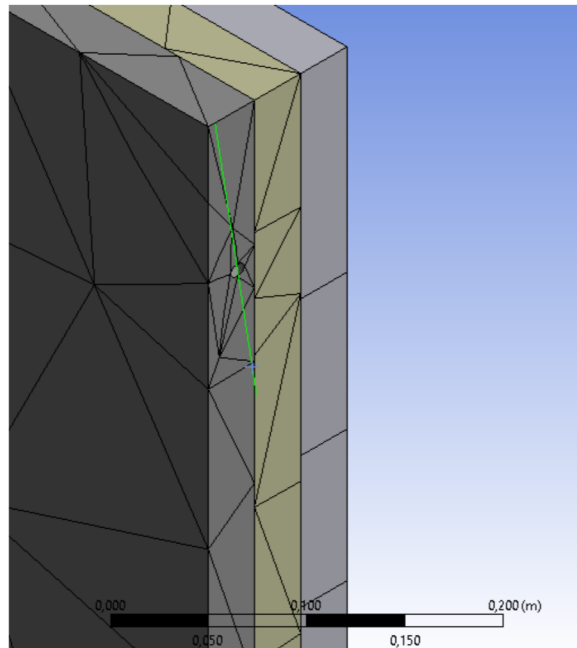


Figure E.3: Visualization of the model with line elements as bolts in one of the CLT panels