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# The behavior of cross-laminated timber and reinforced concrete floors in a multi-story building

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ABSTRACT

The behavior of cross-laminated timber (CLT) and reinforced concrete (RC) floors in a multi-story building is investigated in this article. The load-bearing capacity, fire resistance, and sound insulation characteristics of the floors are the main focus of this research. In order to achieve this goal, a four-story building having RC floors is modeled, analyzed, and designed using the StruSoft FEM-Design software (FEM) following the Eurocodes and Swedish national annex. The building is considered to be in the city of Gävle in Sweden. Then, the RC floors of the building are replaced with the CLT floors, and the same process is done utilizing FEM. The utilization ratios (the ratios of the applied loads to the load-bearing capacities), vertical deflections, weights of the RC and CLT floors, and reaction forces of the buildings are evaluated and compared. The results show that the RC floors meet the deflection requirements well which contribute to the focus on their utilization ratios. The designed RC floors are acceptable from the vertical deflection and utilization ratio perspectives. However, the CLT floors cannot meet the vertical deflection requirements, and thus, need strengthening. The CLT floors are strengthened with supporting timber beams and columns which result in acceptable vertical deflections and utilization ratios. Fire resistance and sound insulation conditions of the RC and CLT floors are assessed by calculations based on the requirements of the Swedish National Board of Housing, Building, and Planning regulations (BBR) as well. The RC floors have the ability to be soundproof and have no difficulties in meeting the fire resistance requirements R60 of BBR. A cross-section is proposed for the CLT floors which can meet the fire resistance requirement R60 and sound insulation requirement C of BBR. The maximum reaction forces of the buildings and total weights of the floors are larger in the case of RC than CLT.



## 1. Introduction

Reinforced concrete (RC) has good properties in terms of stiffness, fire resistance, and sound insulation. The downsides of RC are its heavyweight and severe environmental impact. From an environmental impact aspect, cross-laminated timber (CLT) is a more desirable building material since it has a low environmental impact and good load-bearing capacity in relation to its own weight.

Many studies on CLT panels and floors can be found in the literature. The results of an extensive testing program on the fire behavior of CLT panels were presented by Frangi et al. (2009). Öqvist et al. (2012) conducted field measurements of impact and airborne sound insulation for prefabricated CLT panels. Rolling shear modulus and strength of CLT fabricated with black spruce were measured by Zhou et al. (2014). Design methods of CLT elements subjected to bending were checked experimentally and analytically by Vilguts et al. (2015). Franzoni et al. (2017) analyzed the influence of periodic gaps between lamellas of CLT on the panel's elastic behavior. Pang and Jeong (2019) examined the effects of wood species, thickness and lamina combinations, and span-to-depth ratio on bending strength and stiffness of CLT floor elements. Impact sound insulation tests were performed by Zhang et al. (2020) on CLT and timber-concrete composite floors to evaluate the impact of sound insulation performance. Valdes et al. (2020) experimentally tested a set of CLT panels made of maritime pine

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externally reinforced with natural flax fibers fabrics. The influence of the rolling shear deformation on the flexural behavior of CLT panels was evaluated by Sandoli and Calderoni (2020). Results of experimental tests on the structural behavior, fire behavior, and fire resistance of CLT rib panels were reported by Kleinhenz et al. (2021). de Moraes Pereira et al. (2021) assessed the structural behavior of dowel CLT panels by experimental tests. Morandi et al. (2022) benchmarked methods for the extraction of wavenumber information on CLT plates from which the effective elastic properties to model CLT structures as an equivalent homogeneous plate could be derived.

However, this article aims to examine the load-bearing capacity, fire resistance, and sound insulation features of CLT and RC floors in a four-story building. The StruSoft FEM-Design software (FEM) is utilized in this study to model, analyze, and design the building based on the Eurocodes (ECs) (CEN, 2002a; 2002b; 2004; 2005) and Swedish national annex (EKS) (EKS, 2015). The utilization ratios, vertical deflections, and total weights of the RC and CLT floors are evaluated. Reaction forces of the buildings having the RC and CLT floors are assessed too. Moreover, fire resistance and sound insulation conditions of the RC and CLT floors are investigated using calculations based on the requirements of the Swedish National Board of Housing, Building, and Planning regulations (BBR)†.

## 2. Research methodology

A four-story building with the outer dimensions of 15m×10m was drawn using Revit. The plan and three-dimensional (3D) view of the building are shown in Figs. 1 and 2, respectively. Each story contains two identical apartments that are mirrored each other (Fig. 1). Only load-bearing elements, elevator, and staircase were taken into account in Revit. Then, the same building was modeled in FEM following the ECs and EKS for the city of Gävle in Sweden. Initially, the building was modeled and designed with RC for walls and floors with concrete class C25/30. The thicknesses of the load-bearing walls and floors were chosen to be 200mm and 250mm, respectively. The 3D view of the modeled building in FEM is illustrated in Fig. 3. The floor of each story of the RC building was divided into sub-floors (Fig. 4) in order to facilitate an accurate analysis at a later stage.

When the building was completely modeled, different loads were considered in FEM as listed in Table 1. It is worth mentioning that FEM employed the structural self-weight of the building automatically (Bahrami et al., 2021b). Then, various load cases and load combinations were generated by FEM (Bahrami et al., 2021a). The analysis of the building was done according to the ECs and EKS (Bahrami et al., 2021c), and the building elements were checked for having utilization ratios of a maximum of 100% and acceptable vertical deflections. The obtained results are presented in section 3 of the current article.

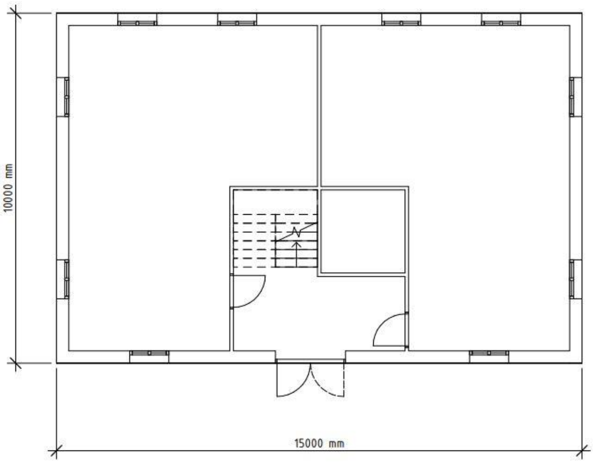


**Fig. 1:** Plan of building in Revit

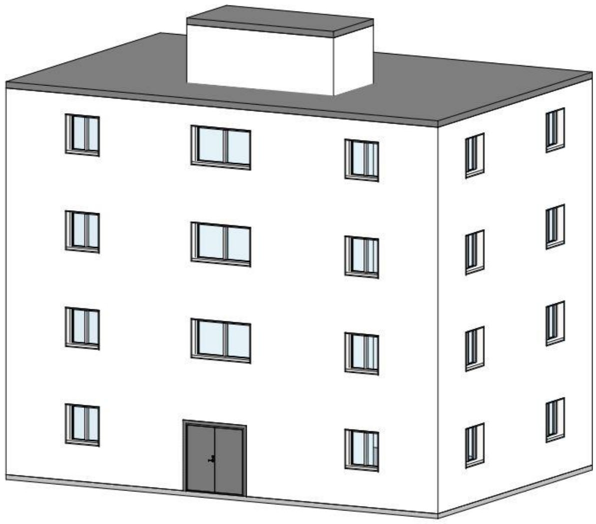

**Fig. 2:** 3D view of building in Revit

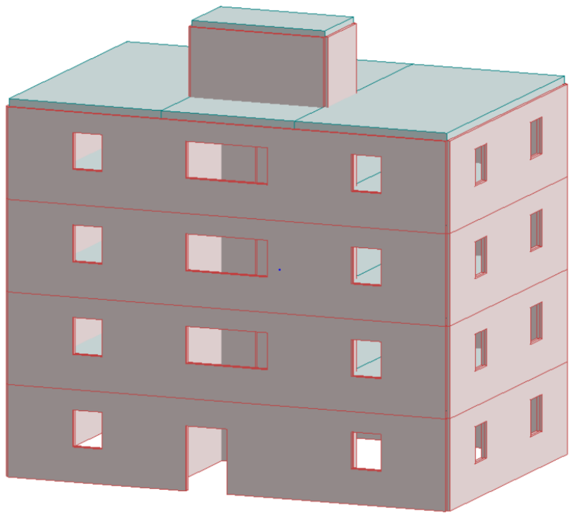

**Fig. 3:** 3D view of modeled building in FEM

Afterward, the same modeled building was adopted in which RC floors were changed to CLT. All the loads of Table 1 were also taken into consideration for this building having the CLT floors

† BFS 2011: 6 (BFS 2020: 4): Regulations and general advice, The National Board of Housing, Building, and Planning, Karlskrona, Sweden

(CLT 170 C5s) except the self-weight of flooring which was obtained as 0.47kN/m² for floors 1, 2, and 3, while half of it was applied to the roof. The same processes of creating load combinations, analysis, and design of this building were conducted as those for the building having the RC floors.

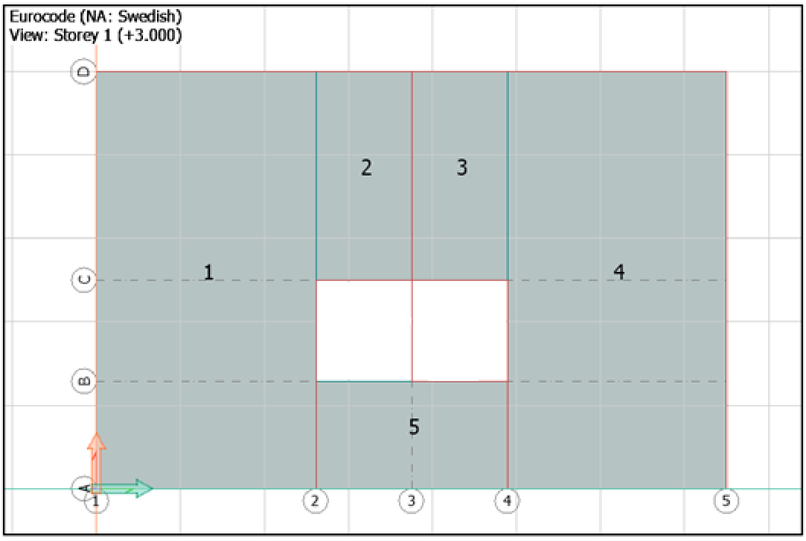


**Fig. 4:** Typical sub-floors of the building having RC floors

**Table 1:** Input data for loads with their locations for the building having RC floors

| Load type | Input data | Location |
|---|---|---|
| Self-weight of non-load-bearing walls on floors | 1.2 kN/m² | Floors 1, 2, 3 |
| Self-weight of flooring | 0.21 kN/m² | Floors 1, 2, 3, 4* |
| Imposed load | 2 kN/m² | Floors 1, 2, 3 |
| Snow load (Zone load) | 2.5 kN/m² | Floor 4 |
| Wind load | Terrain type III, Reference wind speed 23 m/s | Floor 4 and building's perimeter surface |

*Half of the self-weight was applied to the roof

## 3. Results and discussions

The results achieved from the analysis and design of the buildings having the RC and CLT floors are presented and discussed herein.

### 3.1. Building having RC floors

Maximum utilization ratios, vertical deflections, fire resistance, and sound insulation of the RC floors are significant factors that are discussed in this section.

#### 3.1.1. Maximum utilization ratios and vertical deflections

From the structural point of view, the utilization ratio and vertical deflection were very important for the floors. The utilization ratios would be a maximum of 100% and vertical deflections would be within the acceptable range (18mm-40mm, depending on the span length) to have an acceptable design and the floors to function well. The obtained utilization ratios for the floors are displayed in Fig. 5. The green color of the floors reveals their good utilization ratios. In addition, the obtained vertical deflections of the RC floors were demonstrated to be small and within the acceptable range from which the largest vertical deflection occurred in the center of the two large sub-floors 1 and 4. Accordingly, the RC floors were designed appropriately.

#### 3.1.2. Fire resistance

In accordance with the BBR, buildings must be categorized into building classes, Br, based on their need for fire protection. The four-story building of this study was placed in the building class Br1 which had to be designed with the consideration of a great need for the fire protection and must achieve the requirement R60. With an RC floor, there should be no concern regarding the fire. Following the ECs, an RC floor with a thickness of 80mm meets the fire requirement R60. However, the thickness of the RC floors in this building was 250mm which resulted in a fire class that could meet the fire requirement beyond REI 240 based on the ECs, because the requirement for this class is an RC floor thickness of 175mm. Therefore, providing the RC floors with the thickness of 250mm in this building could lead to at least REI 240, and was perfectly acceptable from the fire resistance perspective.

#### 3.1.3. Sound insulation

Since RC insulates sound well, only a suitable covering was needed for the floor to meet the BBR's sound requirements C. A complete RC floor was proposed as in Fig. 6. On this floor, however, a suspended ceiling was also added. This suspended ceiling could contribute to even better sound insulation but had the main goal of hiding installations that would be needed in the ceiling, for example, air conditioning.

### 3.2. Building having CLT floors

When the same sub-floors of Fig. 4 were considered for the building having the CLT floors with a thickness of 170mm, the analysis of the building uncovered that the CLT floors could not carry the loads with the same spans as the RC floors. Therefore, two large sub-floors (1 and 4) of Fig. 4 were divided into smaller sub-floors (1a, 1b, 4a, and 4b) in Fig. 7 for the building having the CLT floors.

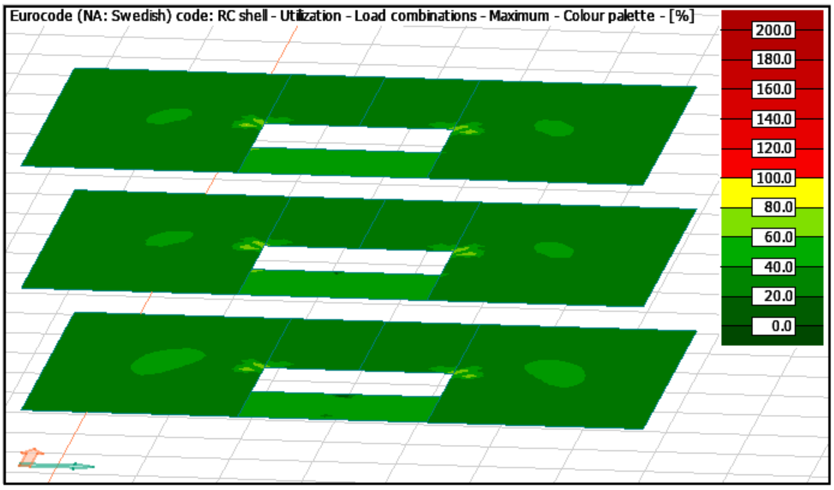


**Fig. 5:** Maximum utilization ratios of RC floors

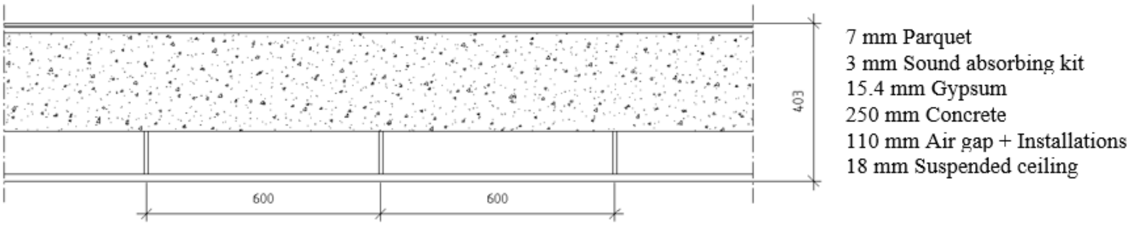


**Fig. 6:** Proposed RC floor for sound insulation (Unit: mm)

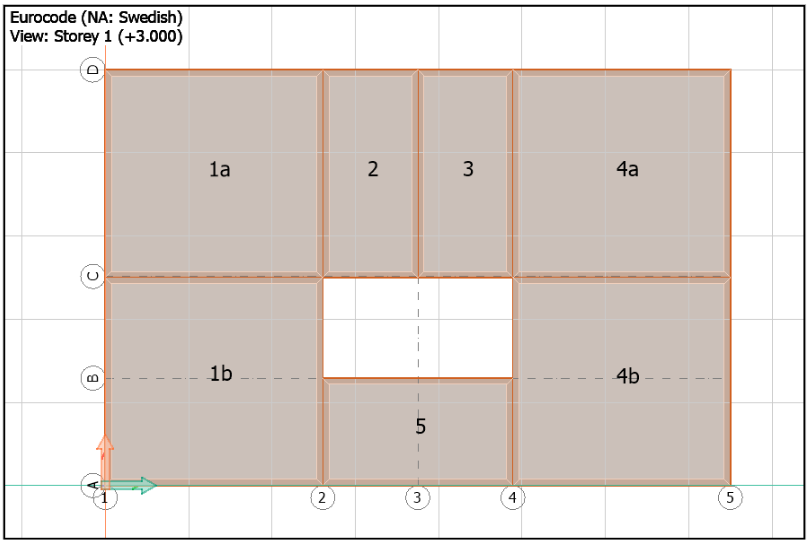


**Fig. 7:** Typical sub-floors of building having CLT floors

#### 3.2.1. Maximum utilization ratios and vertical deflections

The analysis of the building having the CLT floors revealed that the floors had larger vertical deflections than the acceptable range (15mm-17mm, depending on the span length). Due to the vertical deflection requirements, the solution was to support the CLT floors with timber beams and columns as can be seen in Fig. 8. The timber beams were glulam with the dimensions of 78mm×90mm, 42mm×180mm, 115mm×180mm, and 165mm×180mm, and the timber columns were also glulam with the dimensions of 115mm×90mm, 115mm×115mm, and 140mm×135mm. The maximum vertical deflection of the strengthened CLT floors was 15.94mm (Fig. 9) and acceptable. Afterward, the utilization ratios of the CLT floors were obtained which are reported in Fig. 10. The green palette in Fig. 10 indicates the good utilization ratios of the CLT floors.

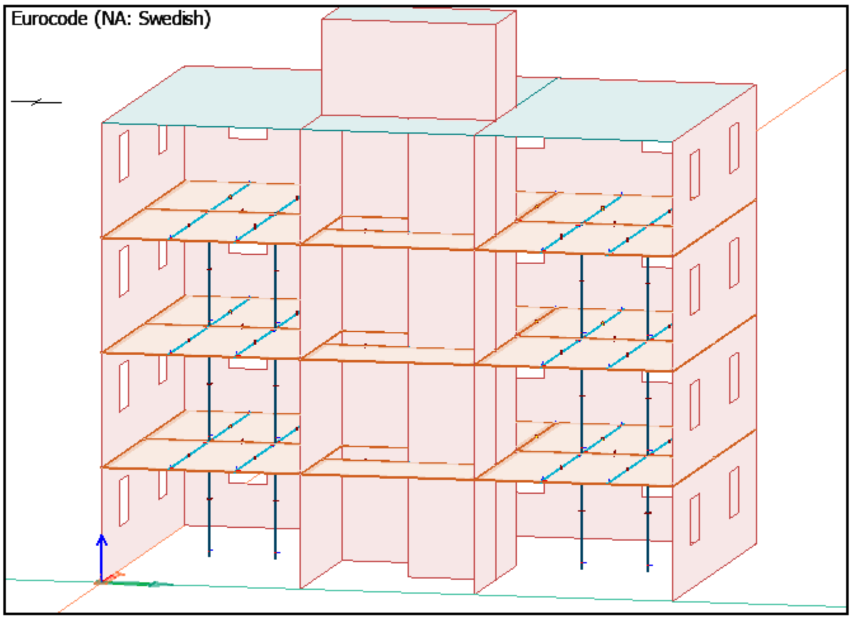


**Fig. 8:** Using beams and columns for strengthening CLT floors

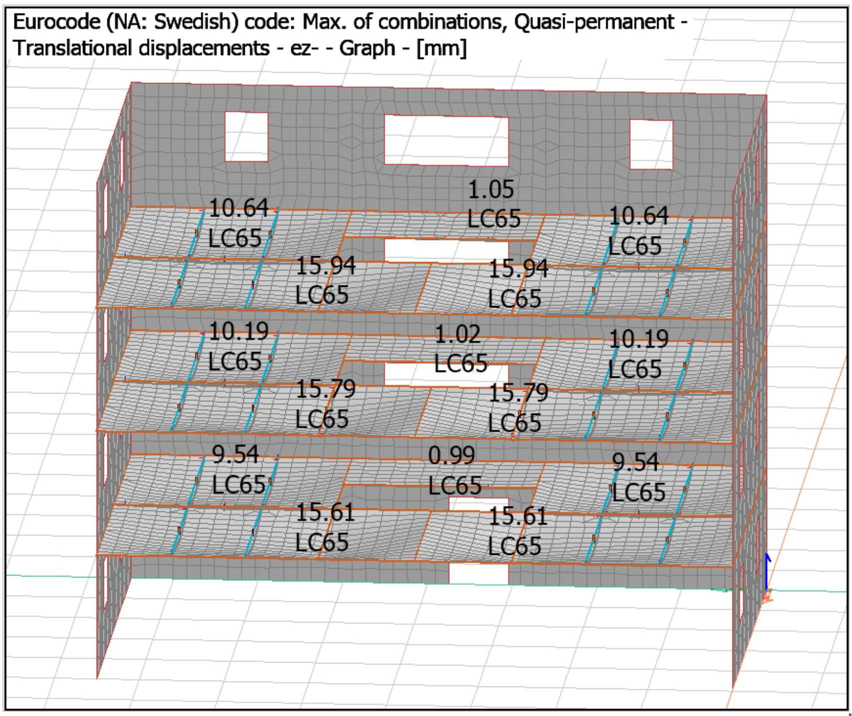


**Fig. 9:** Maximum vertical deflections of CLT floors

### 3.2.2. Fire resistance

In the event of a fire, timber as a frame material can cause concern. But when timber is combined with good fire protection materials, such as gypsum, BBR's fire requirements can be met. In this study, the fire resistance of the CLT floors was checked using the calculations based on the code. According to the calculations, two gypsum boards were applied to the lower edge and one to the upper edge of the floors which resulted in the floors meeting the fire resistance requirement R60. The thickness of the CLT floors would reduce to about 131mm after fire for 60 minutes. Thus, it was uncovered that an effective thickness of 130mm for the CLT floors would suffice for their fire resistance. This thinner cross-section was checked in FEM by replacing the existing CLT floors (170mm) with this new cross-section. The building with the thinner CLT floors was then reanalyzed and it resulted that the utilization ratios of the CLT floors were below 100% and acceptable. The achieved acceptable utilization ratios of the CLT floors with this effective thickness are shown in Fig. 11. Consequently, the previously adopted thickness of the CLT floors as 170mm was approved from the fire resistance aspect.

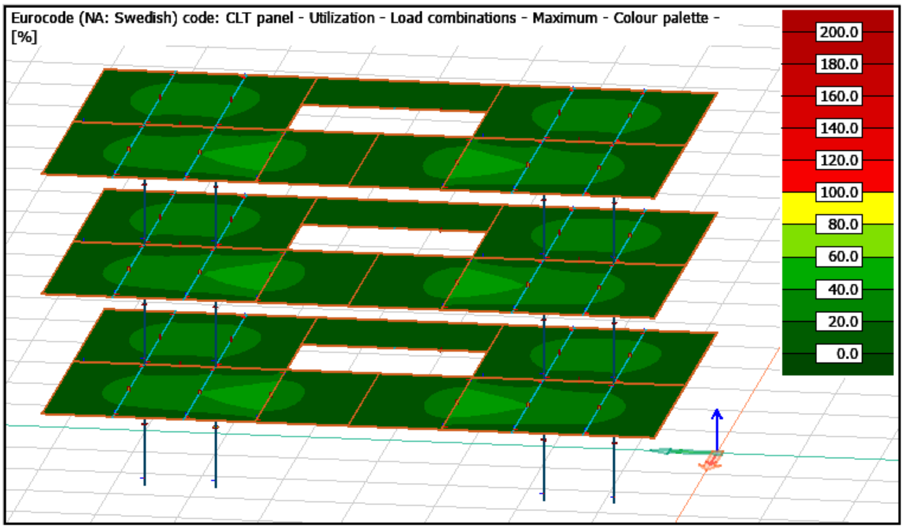


**Fig. 10:** Maximum utilization ratios of CLT floors

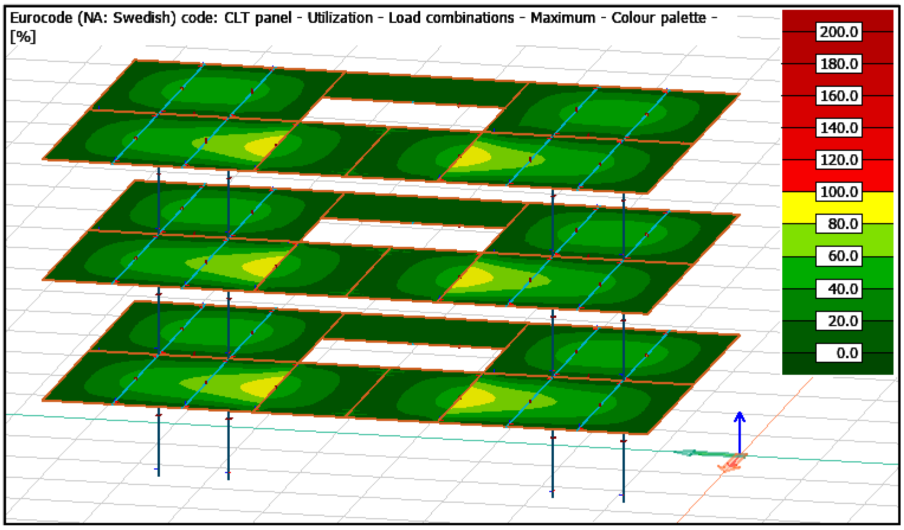


**Fig. 11:** Maximum utilization ratios of CLT floors for fire resistance

### 3.2.3. Sound insulation

The CLT floor had to meet BBR's sound requirements. Since timber is a relatively lighter material than RC, the sound requirements level was harder to reach for the CLT floors. The solution for the sound problem of the CLT floors was to add a 3mm thick sound-absorbing layer on the upper edge and insulation on the lower edge. According to the code, the following floor in Fig. 12 with the needed thicker thicknesses could meet the requirements for the sound class C, which was adopted for the CLT floors.

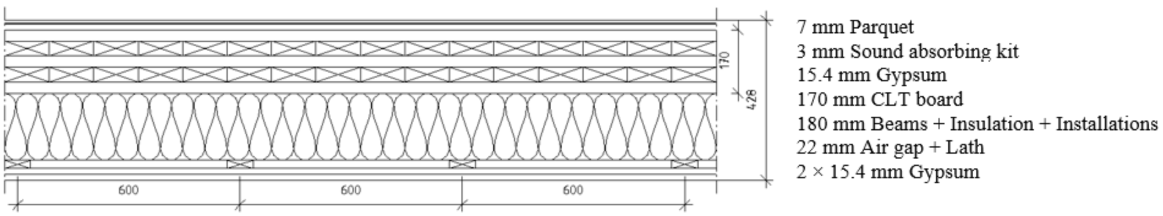


**Fig. 12:** Proposed CLT floor for sound insulation (Unit: mm)

### 3.3. Comparisons of utilization ratios, vertical deflections, reaction forces, and weights

The RC floors could be designed based on their utilization ratio requirements since vertical deflection was not a problem for them thanks to the higher rigidity of concrete than CLT. However, the CLT floors were designed in accordance with the vertical deflection requirements, since the floors could have acceptable utilization ratios, but their vertical deflections were not acceptable. Strengthening the CLT floors using the supporting timber beams and columns mentioned in section 3.2.1 led to their acceptable vertical deflections. However, the vertical deflections of the RC floors were smaller than their corresponding CLT floors. On the other hand, these added columns for the CLT floors took some spaces from the open floors, thus, the RC floors were more favorable from the architectural viewpoint.

The vertical reaction forces of the load-bearing elements of the buildings having the RC and CLT floors were taken from the analyses. The maximum reaction forces are compared in Table 2. Axes mentioned in Table 2 can be observed from Figs. 4 and 7. The largest difference between the maximum reaction forces of the buildings having the RC and CLT floors could be found for the reaction forces of the interior load-bearing walls at 31%. This is not only due to the fact that the RC floors were heavier, but the columns used for the CLT floors could also successfully bring down some parts of the floors' forces to the foundation. The reaction forces of the exterior walls for the building having the CLT floors would have been increased if the forces that the columns transferred to the foundation had been brought down through the exterior walls. In this way, the differences between the reaction forces of the buildings having the RC and CLT floors would have been decreased. Further, the total weights of the structural RC and CLT floors (without additional materials) of the buildings were achieved and compared. It resulted that the total weights of the RC and CLT floors were 86.81t and 9.93t, respectively. Lower reaction forces of the building having the CLT floors than the building having the RC floors could lead to a lighter foundation, and also the lighter weight of the CLT floors compared with the RC floors was structurally desirable. Both of these mentioned issues could finally accomplish cost savings for the building having the CLT floors.

**Table 2:** Differences between maximum reaction forces of buildings having RC and CLT floors

| Location | Building with RC floors (kN) | Building with CLT floors (kN) | Difference (%) |
|---|---|---|---|
| Axis 1 | 222.2 | 161 | 28 |
| Axis 5 | 224.6 | 164 | 27 |
| Axis D | 223.3 | 162 | 27 |
| Axis A | 198.1 | 150 | 24 |
| Interior walls | 220.5 | 153 | 31 |

## 4. Conclusions

A four-story building having RC floors was modeled, analyzed, and designed by the use of FEM based on the ECs and EKS. The utilization ratios and vertical deflections of the RC floors of the building were achieved acceptable while the utilization ratio was the determining factor for the design of the floors. The RC floors of the building were then replaced with the CLT floors. Afterward, this building was again analyzed and designed. In order to achieve acceptable vertical deflections for the CLT floors, they needed to be strengthened. Supporting timber beams and columns were used to strengthen the CLT floors which led to acceptable vertical deflections while having acceptable utilization ratios. The designed RC floors with the thickness of 250mm and the proposed cross-section for the RC floors with the thickness of 403mm had good fire resistance and sound insulation, respectively. Although the RC floors demonstrated good properties in terms of fire and sound, the final cross-section of 403mm was only 25mm thinner than the cross-section of the CLT floors, 428mm. This was because of choosing to hide installations in the ceiling. If the installations were instead hidden in the walls, the difference would have been much greater; because the CLT floors still needed underlying beams as supports with insulation and gypsum to meet sound and fire requirements. Accordingly, the RC floors could be used without the suspended ceiling, which could have reduced the cross-section by 110mm. Then, the cross-sectional difference between the RC and CLT floors would have been 135mm. However, since the RC and CLT floors only differed by 25mm, the building could have about the same story height. The maximum reaction forces of the buildings having the CLT floors and the total weight of the CLT floors were lower than their RC counterparts which were favorable from the structural and economic perspectives.

## Compliance with ethical standards

## Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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