

# Comparison of Cross-Laminated Timber and Reinforced Concrete Floors with Regard to Load-Bearing Properties

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**Abstract** Floors of a building with the relatively new and environmentally sustainable structural material as cross-laminated timber (CLT) and traditional reinforced concrete (RC) are compared in this paper with regard to their load-bearing properties. StruSoft FEM-Design software is utilised to model, analyse and design an existing building using the CLT and RC floors. The building has three stories with a penthouse on the top floor. Modelling, analysis and design of the building can be summarised into five main steps. In step 1, the building with the RC floors is modelled, analysed and designed according to the geometries and specifications of the building. The RC floors of the building are then changed to the CLT floors with the similar thickness and the function of the building is checked for tensile and compressive stresses, utilisation ratio and deflection in step 2. Step 3 involves checking what reinforcing is required for the CLT floors to be approved with about the same thickness as the RC floors. In step 4, it is controlled whether a larger thickness of the CLT floors without reinforcing can withstand the identical conditions of the RC floors. From the obtained results, effects of thickness of the CLT floors and span width are examined. The structural stability of the building with the CLT and RC floors is controlled in step 5. Further, the CLT and RC floors of the building are compared in terms of their stresses, utilisation ratios and weights. The results of this paper demonstrate advantages of using the CLT floors. The CLT floors show good

strength properties compared with their low weights. It is uncovered that the building with both of the CLT and RC floors is stable. Obtained results of the building with the CLT and RC floors from the StruSoft FEM-Design software are compared with those from calculations based on Eurocode 2 and Eurocode 5, which reveal good agreements with each other regarding their accuracy.

**Keywords** Cross-Laminated Timber Floor, Reinforced Concrete Floor, Tensile and Compressive Stresses, Utilisation Ratio, Weight, Structural Stability

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## 1. Introduction

As the population in Sweden increases, high demands are placed on the production of new buildings and in particular housing. At the same time, as the need for housing and construction is getting larger in parts of the country, it has been found that the carbon dioxide in the atmosphere coming from the construction industry is significant. Thus, stronger measures should be taken to keep the emissions of the construction industry down in order to obtain environmental quality objectives which include a good built environment.

Concrete is a well-established material with good strength properties which has been used in the

construction of multi-storey buildings, however, a lot of energy is required during its production. On the other hand, a large part of the greenhouse gas emissions comes from the concrete production. But, wood is an environmentally friendly material, whilst, concrete has had a larger market share than that of wood for a long time since wood has mostly been used for lightweight structures such as single-family houses and decorations of larger buildings. Recently, innovative manufacturing methods have given wood new properties that enable its increased usability in several areas [1]. Therefore, there is a great interest in replacing concrete with wood.

In the mid-1960s, the introduction of a novel wood-based product as engineered wood product (EWP) re-emerged the interest in timber structures. After subsequent development incentives, a new composite product as cross-laminated timber (CLT) was introduced in the mid-1990s. CLT is made up of boards or lamellae that are placed crosswise in several layers. The neighbouring boards are most often glued at an angle of  $90^\circ$  to one another. The thickness of the boards is mostly between 20-60 mm and the number of layers differs between different manufacturers, but usually 3, 5, 7 or more odd layers of boards are used. This is because it is desired to have the highest strength of the material in the main bearing direction, which for wood is along the fibres for both compression and tension. This multi-layered and optimised CLT provides such in-plane and out-of-plane load-bearing capacity that it can be applied as floor panels in the structures [2].

In the last two decades, there has been a development in Swedish structures so that CLT has become increasingly prominent as a structural material mainly due to its strength properties and also its environmental benefits.

CLT panels and floors have been investigated in research projects throughout the world [3-16]. Whereas, CLT and traditional reinforced concrete (RC) floors of an existing building are examined with respect to their load-bearing properties in the current research. Modelling, analysis and design of the building are carried out employing the StruSoft FEM-Design software. Effects of the thickness of the CLT floors and span width are evaluated. Control of the structural stability of the building with the CLT and RC floors is also done.

Moreover, stresses, utilisation ratios and weights of the CLT and RC floors of the building are compared. Comparison is made between the obtained results from the numerical modelling and those from the calculations following Eurocode 2 (EC2) [17] and Eurocode 5 (EC5) [18] for the building having the CLT and RC floors.

## 2. Methodology

An existing building was used as a reference building on which this study was conducted. The methodology of the study is presented in the following.

### 2.1. Reference Building

Figure 1 shows the three-dimensional (3D) plan of the reference building which was taken from the consulting company BTKon. In accordance with the figure, the building has two wings, from which one wing was considered for the investigation in the current study, as shown in Figures 2-4. The red line in Figure 2 illustrates the assumed wall that divides the building. Figure 5 demonstrates the assembly drawing which was utilised to achieve sizes of the floor elements.

### 2.2. Finite Element Method

StruSoft FEM-Design software was employed in the current research to model, analyse and design the reference building. It is an advanced modelling software using the finite element method (FEM). The software has been designed for analyses of reinforced concrete, steel and wood structures, and is adapted to Eurocodes. The Swedish national annex of Eurocode can be used in the software as well. In the software, all parts of the structures such as beams, columns, braces, floors, supports, etc., can be modelled. Loads such as snow, wind and imposed loads are placed based on their geographical locations. Load combinations are generated. Mesh is generated automatically and its mesh size is refined around layouts and connections for increasing accuracy. This can also be set manually.

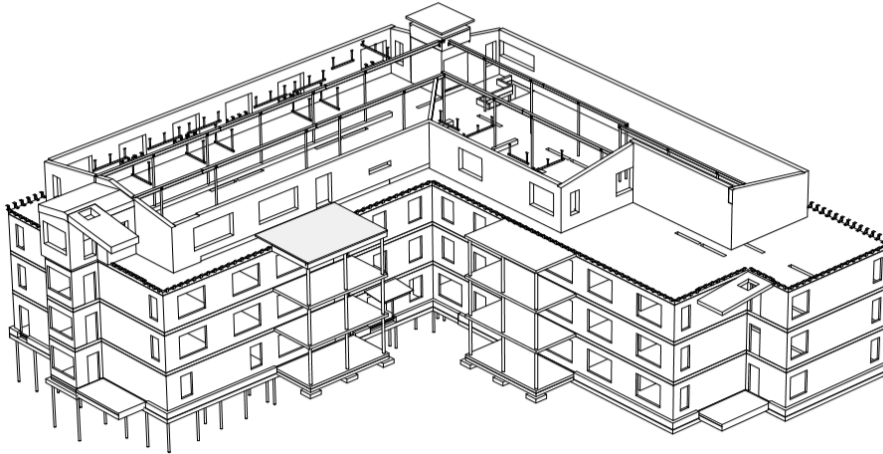


Figure 1. Reference building in 3D

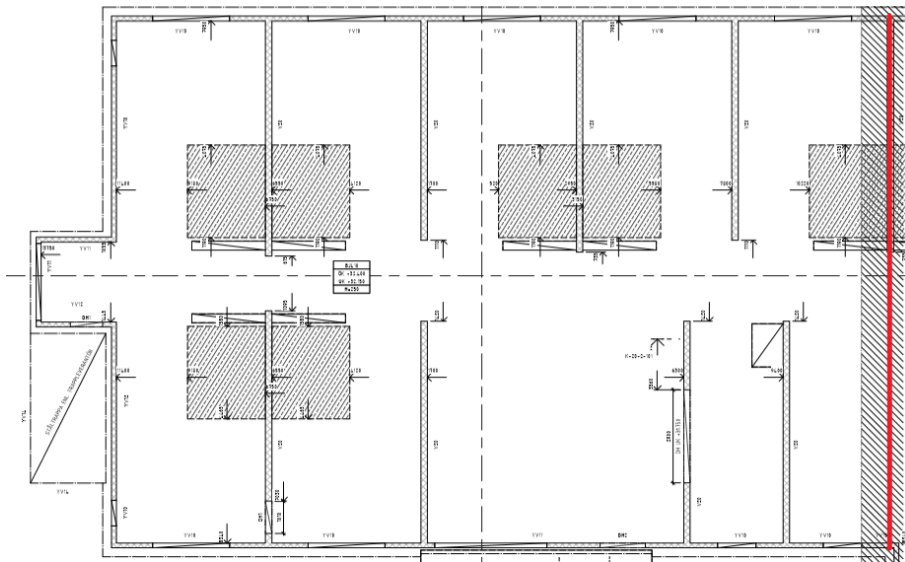


Figure 2. Plan 1

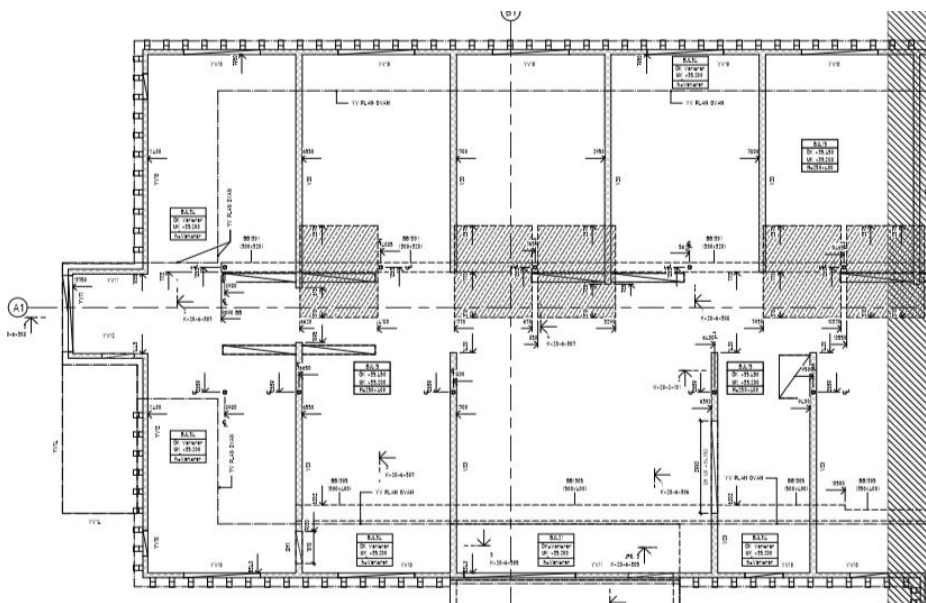


Figure 3. Plan 2

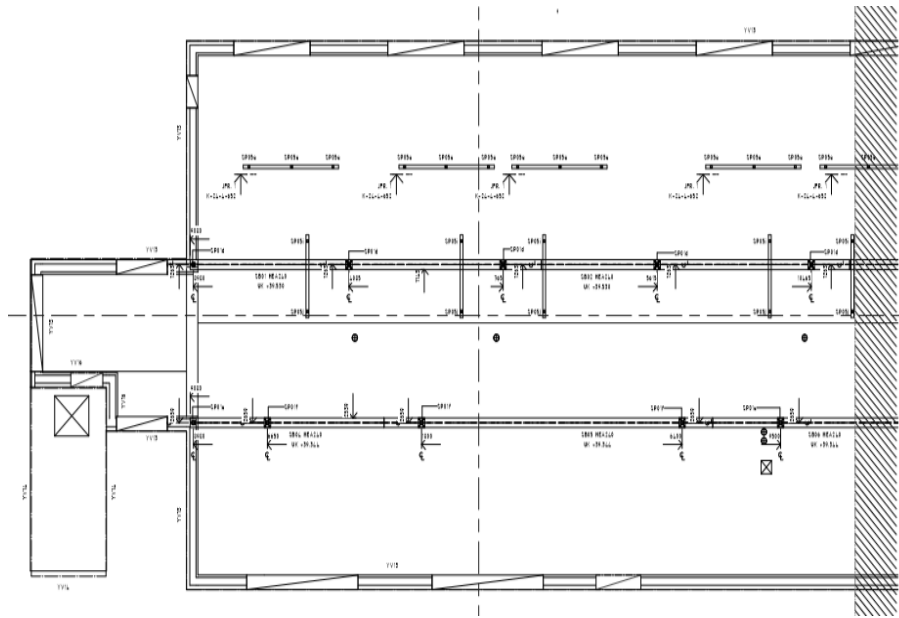


Figure 4. Plan 3 (Roof)

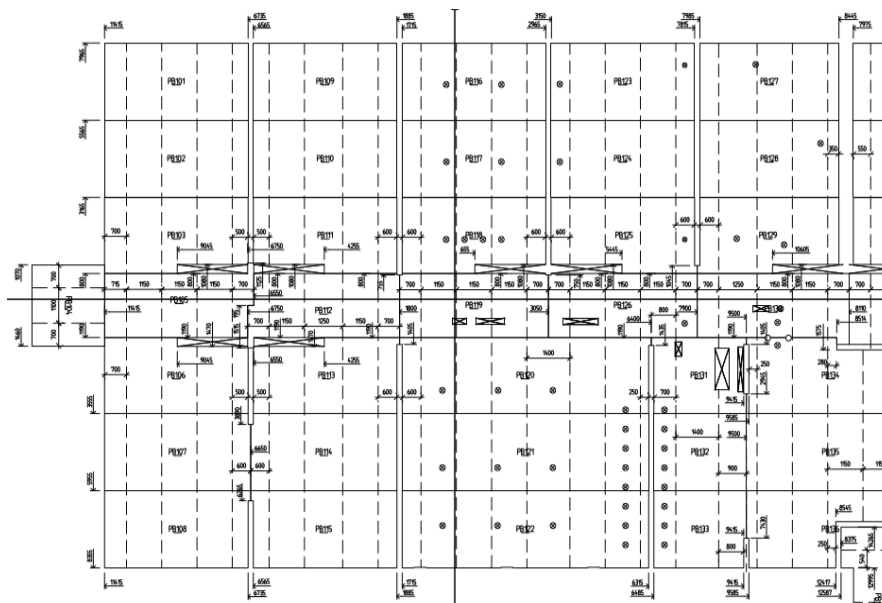


Figure 5. Assembly drawing of floors

### 2.2.1. Building with RC Floors

In the StruSoft FEM-Design software, the geometry of the reference building was modelled. Supports were considered using the line support group, which took rotations and forces in three dimensions into account. Load-bearing exterior RC walls were modelled with the thickness of 150 mm according to the geometry of the building with concrete C30/37, the creep ratio of 2.8 and the shrinkage ratio of 0.4‰ following the national annex of EC2. Load-bearing interior RC walls had 200 mm thickness with concrete C30/37. Dimensions of openings in the walls in the form of windows and doors as well as the geometry of the extended penthouse were considered

on the basis of the building drawings. The floors were modelled with dimensions in accordance with the reference building too. Intermediate floors had a thickness of 250 mm and consisted of flat RC slabs. When designing RC, the software applies reinforcements where they make the greatest use with regard to the choices such as possible steel reinforcement, covering layers and spacing. Reinforcement can be checked, among other issues, against deflection and cracking. The penthouse of the building consisted of a lightweight structure which was modelled with walls of structural timber C24 having struts with the centroid space of 600 mm. Interior load-bearing horizontal beams of the penthouse were

considered as HEA 240, which rested on vertical VKR 100×100×10 based on the reference building. Figures 6-9 indicate the modelled facades. The utilised loads and weights of the materials were obtained from BTKon. Table 1 lists the considered loads.

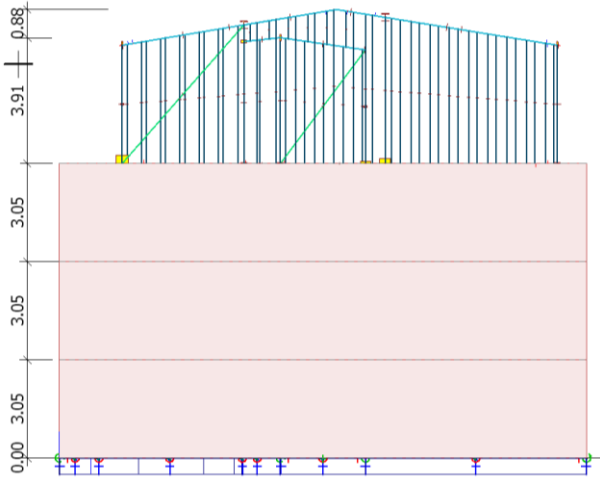


Figure 6. Facade towards X- (unit: m)

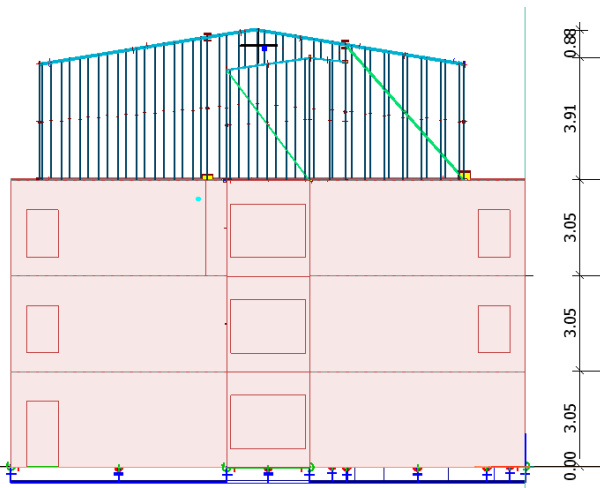


Figure 7. Facade towards X+ (unit: m)

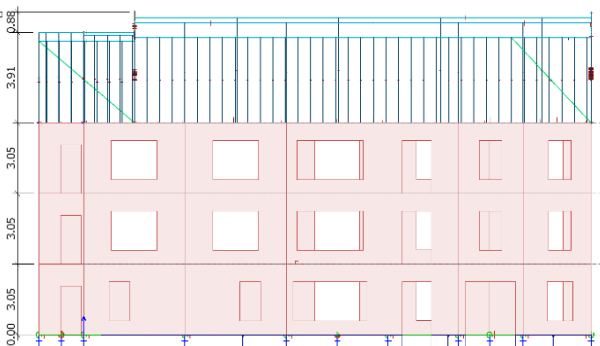


Figure 8. Facade towards Y+ (unit: m)

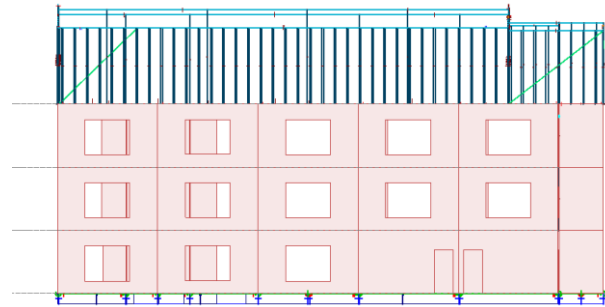


Figure 9. Facade towards Y-

Table 1. Loads used in modelling

Load type	Load consideration
Roof	1 kN/m <sup>2</sup>
Imposed load	2 kN/m <sup>2</sup>
Roof service	0.4 kN/m <sup>2</sup>
Snow load	2 kN/m <sup>2</sup> (zone load)
Wind load	24 m/s (reference wind speed)

The next step was the loads as dead, imposed, snow and wind that were applied to the building. The load cases were grouped and their appropriate partial coefficients were selected. Permanent load was allocated to the building's parts and the roof structure. The remaining loads were assumed to be temporary. The surfaces were loaded with the imposed load of 2 kN/m<sup>2</sup> which was applied as a distributed load. The snow load of 2 kN/m<sup>2</sup> was applied to the roof and roof terraces. The wind load was generated by the wind function of the software having the wind speed of 24 m/s and terrain type II, and was then applied to the building. Afterwards, the software varied the current loads into combinations to accomplish the most unfavourable one. A suitable mesh was generated and the analysis was performed having the standard elements with 4/3/2 nodes. Figure 10 elaborates the building with the mesh. Finally, the analysis and design of the building's elements were carried out.

### 2.2.2. Building with CLT Floors

There is an option in the software to choose the desired CLT panels from various CLT panels that exist in its library with a lot of dimensions from different manufacturers. A material library developed with the most common suppliers is also available. Setra has a wide range of CLT which is available in the library of the software. When choosing the dimension of CLT flooring in this study, Setra's range for CLT flooring was considered. The CLT module makes it possible to calculate and analyse laminated structures with regard to the orthotropic properties of wood, which enables rotation of the material so that different properties of the material can be taken into account depending on the direction. When changing the floors of the building from RC to CLT, the CLT elements were adopted to be the same size as the flat layers with the widths of 2.4 m and lengths according to the reference building. Joints of the floors were assumed

to be simply supported. Other structural elements of the building, the loads, supports and mesh were kept similar to those mentioned in section 2.2.1. The modelled building with the CLT floors is depicted in Figure 11.

### 3. Results and Discussions

The building with RC floors and then CLT floors was analysed. The results were achieved from the analyses, which are presented in the following.

#### 3.1. Stresses in RC Floors of Building

Stresses in the RC floors of the building are investigated here. Walls and floors were designed with concrete having reinforcement of  $\phi 10@150$  where the software was also allowed to design with the compressive reinforcement if required. To meet the utilisation ratio below 100%, the software was allowed to automatically use other reinforcement dimensions. The utilisation ratios below 100% could be met. Figures 12-23 display the outputs regarding the distribution of stresses in the RC floors in the  $x'$  and  $y'$  directions.  $x'$ -top which is the primary direction of the floors shows compressive stresses in the spans and tensile stresses at the supports.  $x'$ -bottom illustrates tensile stresses of the floors in the spans and compressive stresses at the supports.  $y'$ -top and bottom stresses were calculated as the secondary direction across the floor elements.

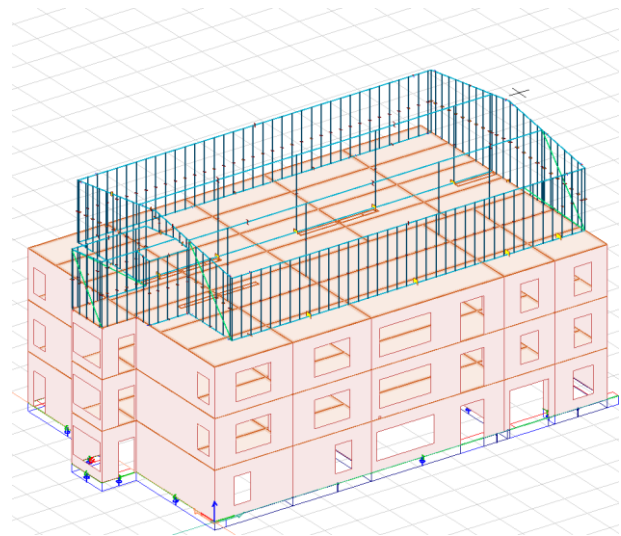


Figure 11. Modelled building with CLT floors

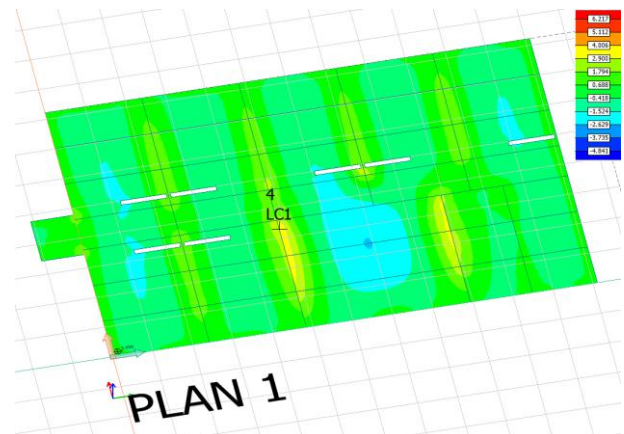


Figure 12. Stress distribution, Sigma  $x'$ , top+

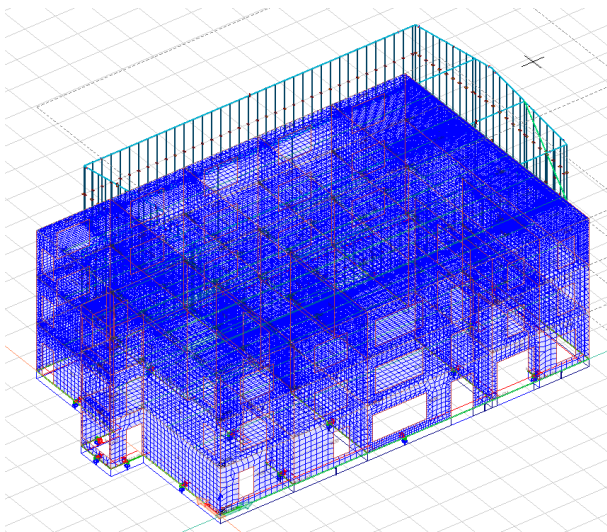


Figure 10. Building with mesh

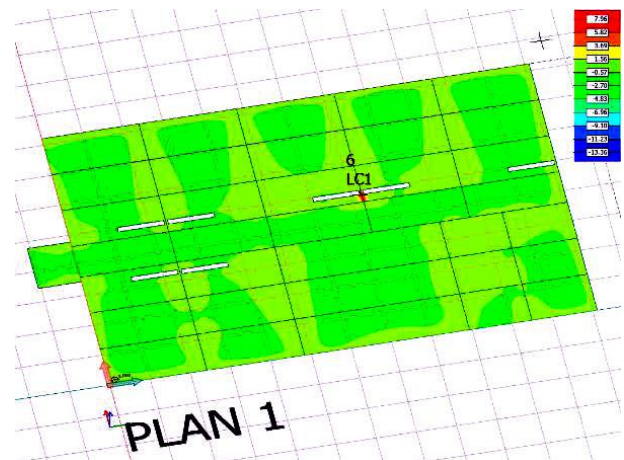


Figure 13. Stress distribution, Sigma  $y'$ , top+

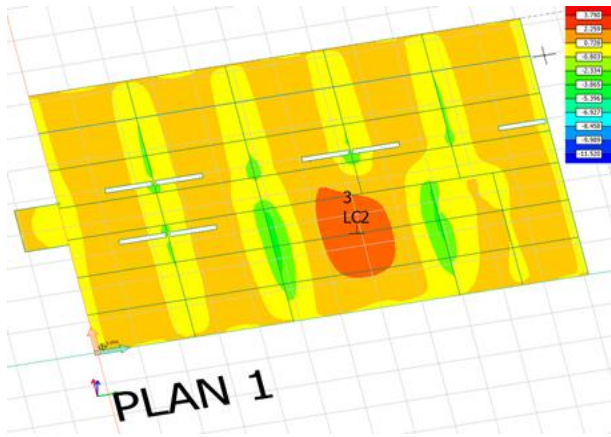


Figure 14. Stress distribution, Sigma x', bottom+

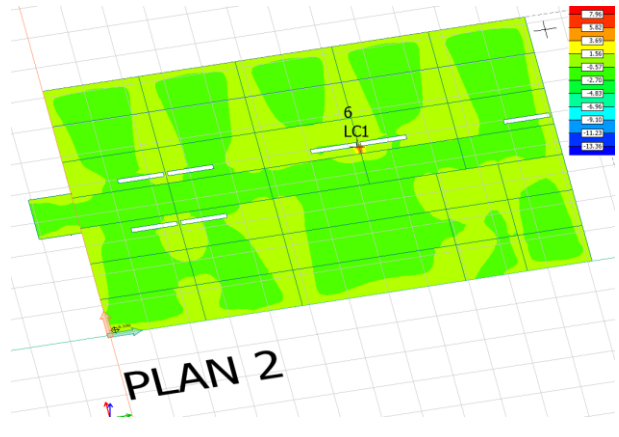


Figure 17. Stress distribution, Sigma y', top+

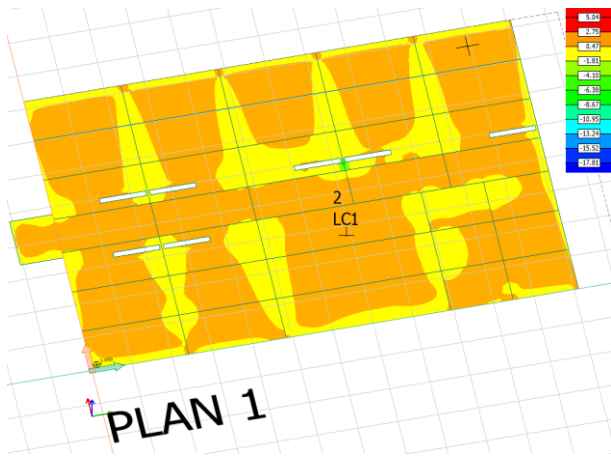


Figure 15. Stress distribution, Sigma y', bottom+

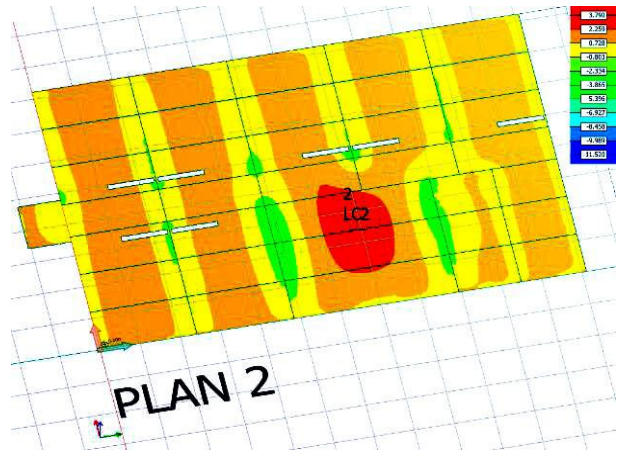


Figure 18. Stress distribution, Sigma x', bottom+

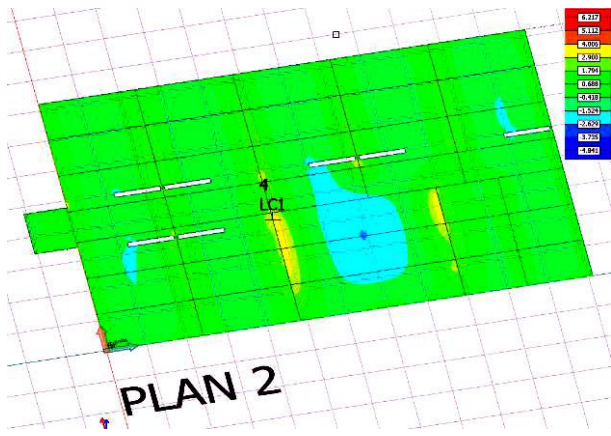


Figure 16. Stress distribution, Sigma x', top+

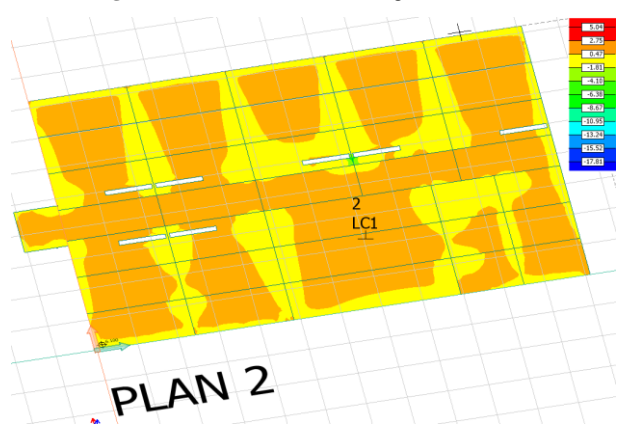


Figure 19. Stress distribution, Sigma y', bottom+

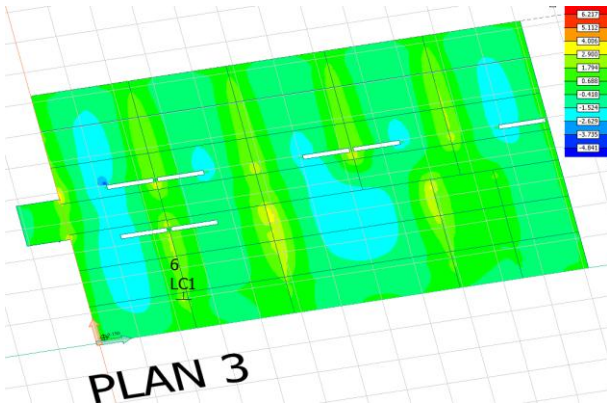


Figure 20. Stress distribution, Sigma x', top+

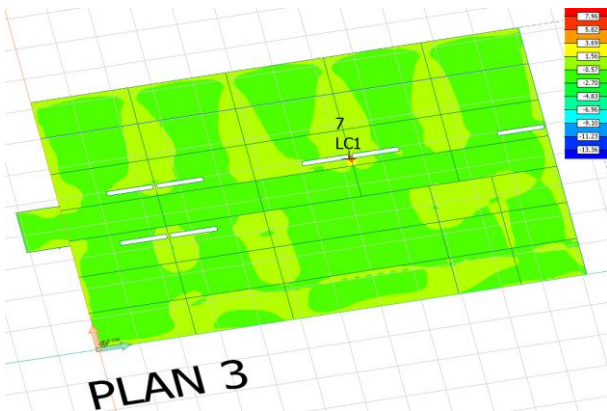


Figure 21. Stress distribution, Sigma y', top+

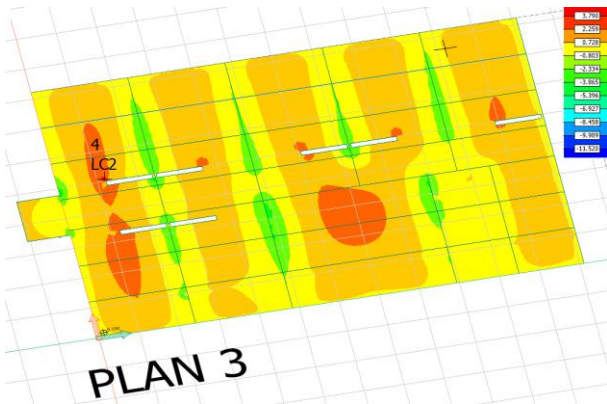


Figure 22. Stress distribution, Sigma x', bottom+

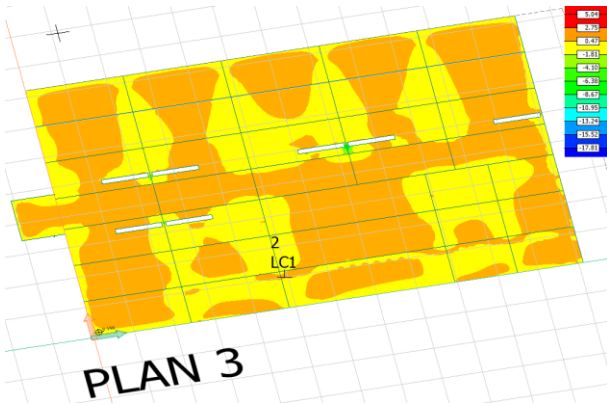


Figure 23. Stress distribution, Sigma y', bottom+

### 3.2. Stresses in CLT Floors of Building

Several attempts were made by using CLT elements with different numbers of layers to obtain the acceptable utilisation ratios. Finally, seven-layer CLT elements with 260 mm thickness could accomplish acceptable utilisation ratios with a comparable thickness of the RC floor, which were taken as the CLT floors of the building. The typical stresses in the CLT floors of the building are shown in Figures 24-33.

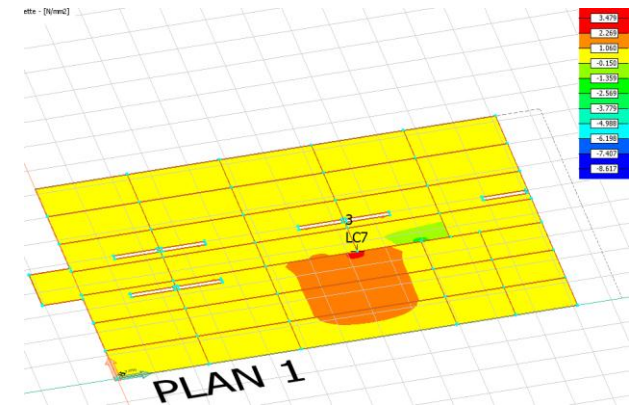


Figure 24. Stress distribution, Sigma x', top+

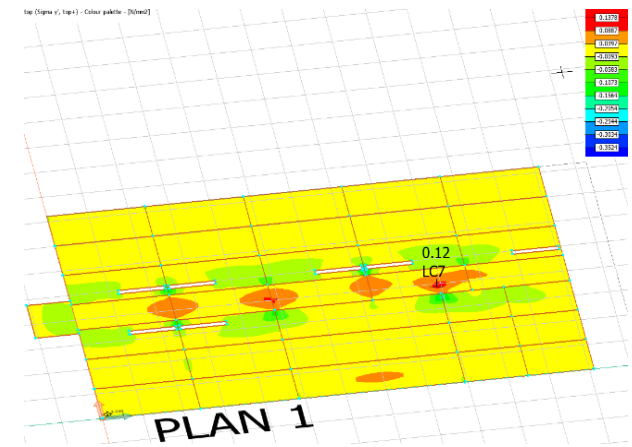


Figure 25. Stress distribution, Sigma y', top+

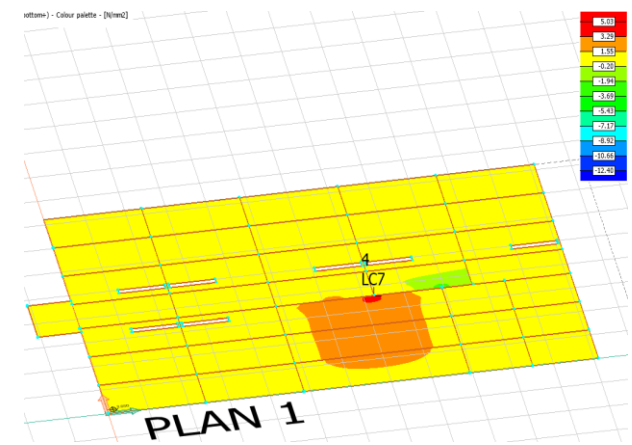


Figure 26. Stress distribution, Sigma x', bottom+

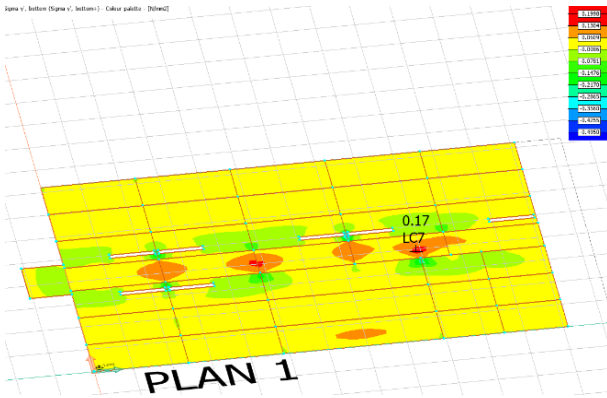


Figure 27. Stress distribution, Sigma y', bottom+

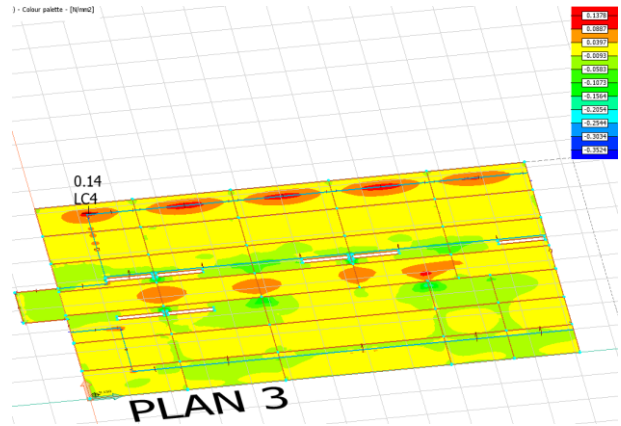


Figure 31. Stress distribution, Sigma y', top+

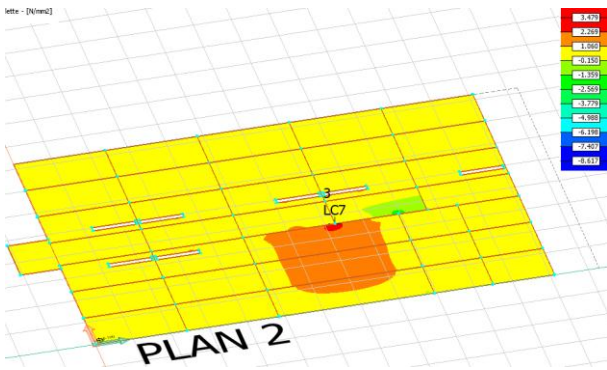


Figure 28. Stress distribution, Sigma x', top+

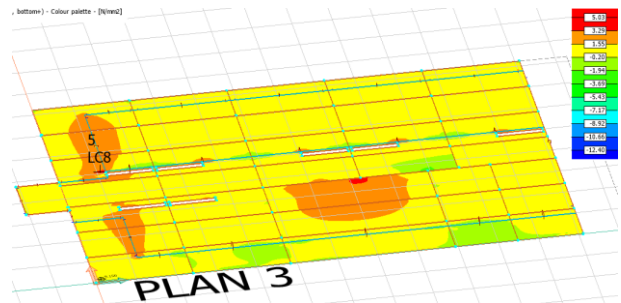


Figure 32. Stress distribution, Sigma x', bottom+

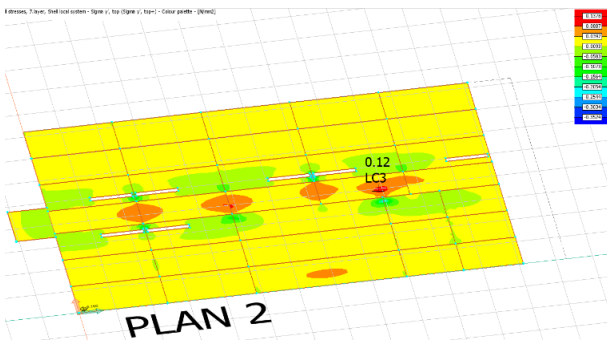


Figure 29. Stress distribution, Sigma y', top+

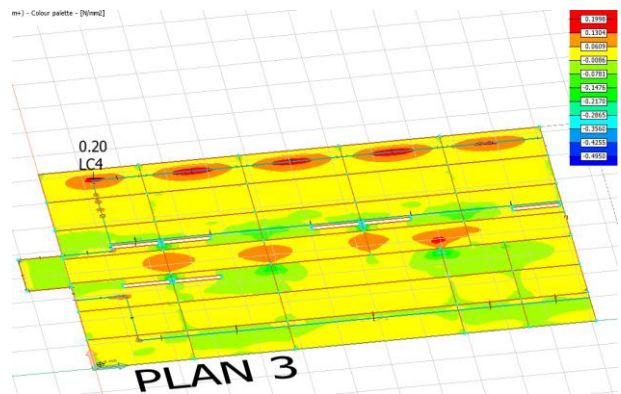


Figure 33. Stress distribution, Sigma y', bottom+

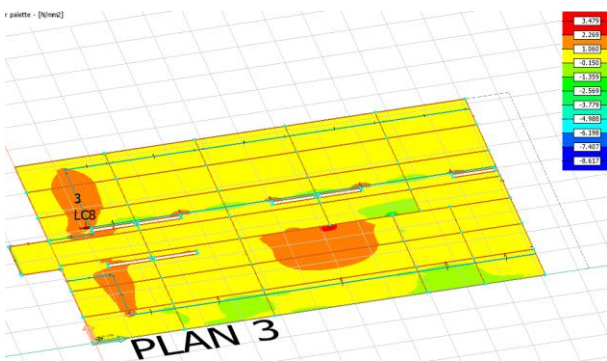


Figure 30. Stress distribution, Sigma x', top+

### 3.3. Utilisation Ratios of RC Floors of Building

The utilisation ratios of the RC floors of the building were controlled to be below 100%. The obtained utilisation ratios of the floors are illustrated in Figures 34-36 which are below 100% and consequently acceptable.

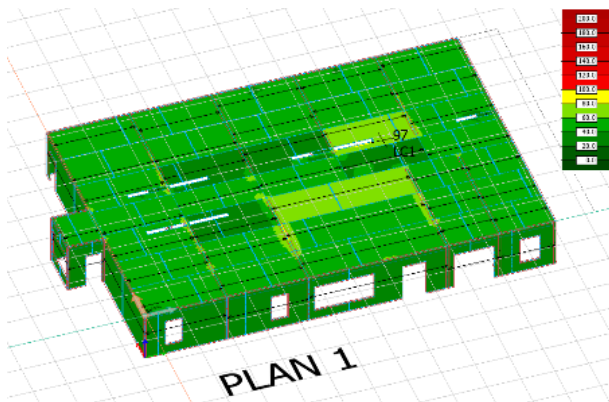


Figure 34. Utilisation ratio of RC floor, 97%

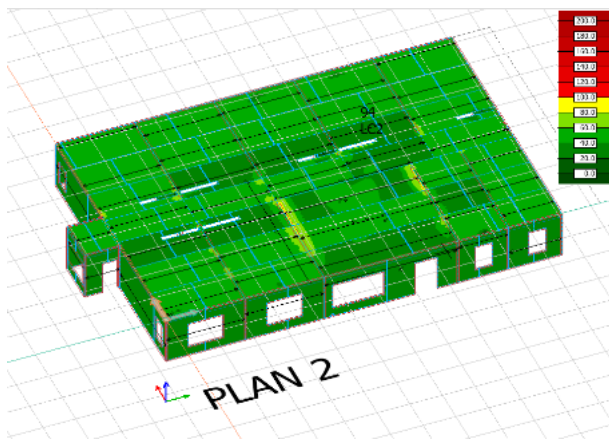


Figure 35. Utilisation ratio of RC floor, 94%

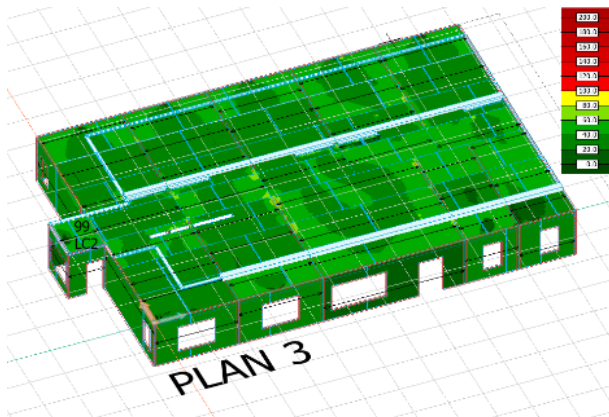


Figure 36. Utilisation ratio of RC floor, 99%

### 3.4. Utilisation Ratios of CLT Floors of Building

The utilisation ratios of the CLT floors for plans 1, 2 and 3 of the building were checked that were 124%, 123% and 118%, respectively. Since these utilisation ratios were above 100%, therefore, they were not acceptable which implied that the CLT floors needed to be reinforced to meet the utilisation ratios below 100%.

Figure 37 demonstrates that the utilisation ratio was too high (124%) between two installation openings. An alternative reinforcing was in the form of a short

supporting beam with the dimensions of  $b \times h \times l$  as 200 mm  $\times$  250 mm  $\times$  400 mm, which was tested under the floor of plan 1 according to Figure 38. Then, it was resulted in the utilisation ratio being reduced from 124% to 92% (Figure 39).

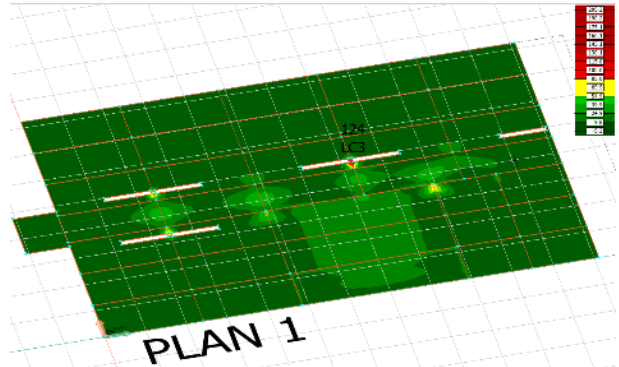


Figure 37. Utilisation ratio of CLT floor before reinforcing, 124%

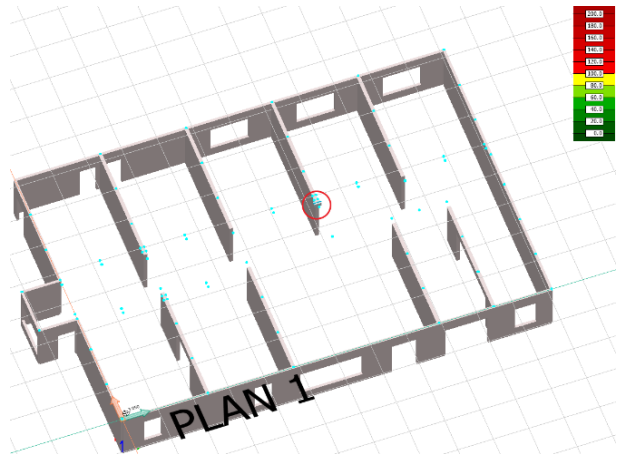


Figure 38. Reinforcing number 1 for CLT floor

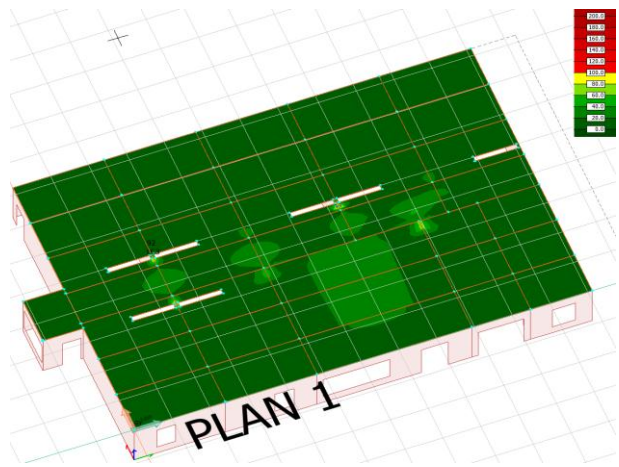


Figure 39. Utilisation ratio of CLT floor after reinforcing, 92%

Also, the utilisation ratio of the floor of plan 2 was 123%, as can be seen from Figure 40. The floor was supplemented with a supporting beam (number 2) and the same short supporting beam (number 1) which was

explained for plan 1. These reinforcing solutions can be observed from Figure 41. Afterwards, the floor could achieve the utilisation ratio of 94% in accordance with Figure 42.

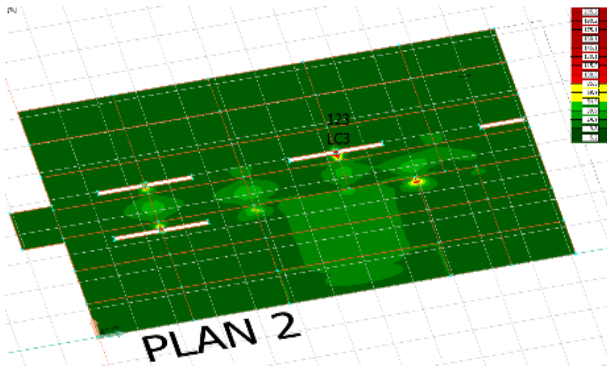


Figure 40. Utilisation ratio of CLT floor before reinforcing, 123%

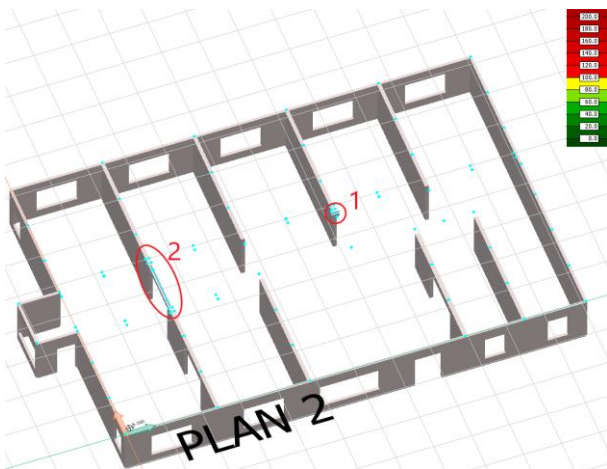


Figure 41. Reinforcing numbers 1 and 2 for CLT floor

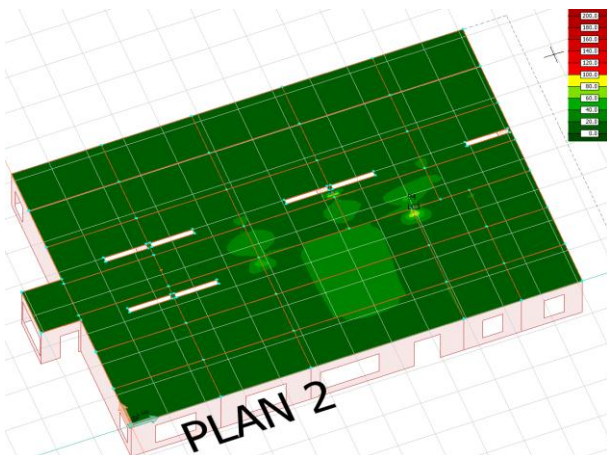


Figure 42. Utilisation ratio of CLT floor after reinforcing, 94%

Moreover, the utilisation ratio of the floor of plan 3 was 118% (Figure 43). The adopted reinforcing solutions for this floor are indicated in Figure 44. The reason for reinforcing number 3 was due to the applied load from the penthouse. Figure 45 clarifies that the utilisation ratio of the floor was 99% after reinforcing.

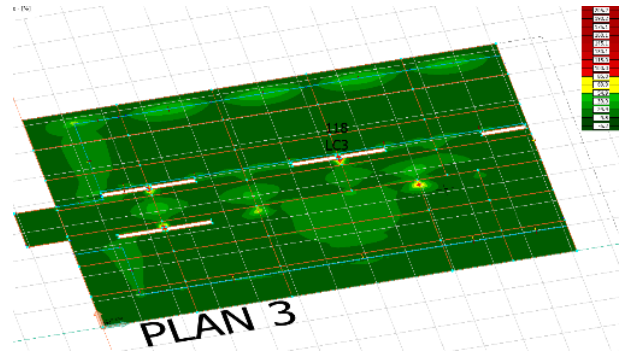


Figure 43. Utilisation ratio of CLT floor before reinforcing, 118%

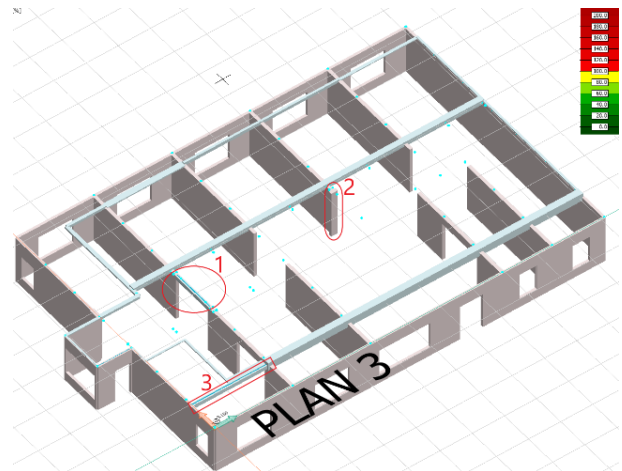


Figure 44. Reinforcing numbers 1, 2 and 3 for CLT floor

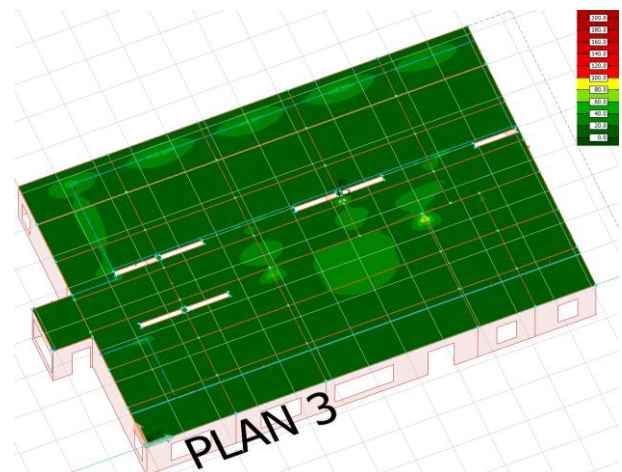


Figure 45. Utilisation ratio of CLT floor after reinforcing, 99%

### 3.5. Effects of Thickness of CLT Floors and Span Width

The effect of thickness of the CLT floor was also evaluated. The thickness of the CLT floor was changed using Setra Group's material library from the software, until the floor elements had the utilisation ratios below 100%. Existing dimensions are 270 mm-300 mm. However, the thickness of 280 mm had the utilisation ratio of 114% for one of the floors. The thickness was

changed for more steps to 300 mm which resulted in the maximum utilisation ratio of 99%. Therefore, the CLT floors with the thickness of 300 mm could lead to the acceptable utilisation ratios without the need for any reinforcing.

Spans between 7.7 m to 10 m were examined with respect to their deflections in quasi-permanent load combinations. The controlled floors were made of RC and CLT with the thicknesses of 250 mm and 300 mm, respectively. The CLT floors tended to deflect more than the RC floors. It was due to their difference in the material's properties such as density and bending stiffness based on moment of inertia and modulus of elasticity. Concrete has a higher bending stiffness than CLT, which can be the reason why the CLT floors had larger deflections. On the plans, walls that carried the loads from the longest floor elements were moved. A total of three elements were affected with 8.2 m in the ordinary design (Figure 46). The wall that is marked in green and extends over all the floors is the wall which was moved. The yellow-marked floor elements were checked for their deflections and the controlled elements were located in the building as depicted in Figure 47.

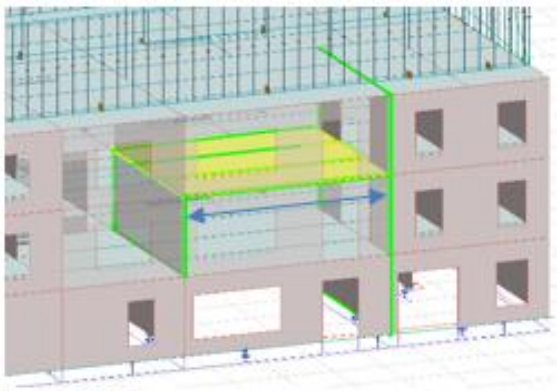


Figure 46. Moved wall

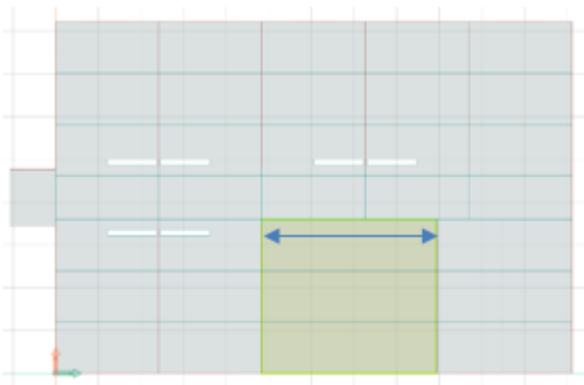


Figure 47. Current element

### 3.6. Stability of Building

Meanwhile, stability of the building was checked. It was shown that the building with both the RC floors (250 mm) and CLT floors (300 mm) was stable based on the stability control in the software. The most critical load combination for the building with the RC floors consisted of LC4ULS which means the load case 4 in the ultimate limit state STR 6.10b according to the Swedish national annex of Eurocode 0 (EC0) [19]. The same load combination was the most critical one for the building with the CLT floors as well. However, the stability of the building was decreased with lighter weight and larger deflection of the floors, thus, the results uncovered that the building with the RC floors was more stable than the building with the CLT floors in accordance with the global analysis.

### 3.7. Comparison of Results of RC and CLT Floors of Building in Terms of Stresses, Utilisation Ratios and Weights

According to the compressive and tensile stresses in the RC and CLT floors, it was witnessed that the RC floors were stiffer generally with higher compressive stresses than the CLT floors, on the other hand, the latter had higher tensile stresses. The higher tensile stresses of the CLT floors than the RC floors were decreased with increasing the cross-section. One reason why some of the RC floors were subjected to less stresses than the CLT floors in the x'-direction was because their capacity across y'-direction was used more than that in the CLT floors.

The summarised results are presented in Table 2 for the RC and CLT floors of the building in terms of the utilisation ratios and weights. As was mentioned previously, when the utilisation ratios of the CLT floors were too high, they were lowered by reinforcing solutions such as adding beams under the floors or moving the walls of the large spans. Also, the thickness of the CLT floors was needed to be increased to have lower utilisation ratios than 100%.

Total weights of the RC floors with the thickness of 250 mm and the CLT floors with the thickness of 300 mm were obtained as 765 t and 150 t, respectively which implied having a difference of 615 t. Lower weight of CLT is advantageous which can lead to fast construction processes compared with RC that requires installation of reinforcement and drying time.

**Table 2.** Comparison of utilisation ratios and weights of RC and CLT floors of building

Plan	RC floor with thickness of 250 mm		CLT floor with thickness of 260 mm after reinforcing		CLT floor with thickness of 300 mm	
	Utilisation ratio (%)	Weight (t)	Utilisation ratio (%)	Weight (t)	Utilisation ratio (%)	Weight (t)
Plan 1	97	255	92	44	90	50
Plan 2	94	255	94	44	90	50
Plan 3	99	255	99	44	99	50
Total		765		132		150

### 3.8. Comparison of Results from Calculations Based on Eurocodes and StruSoft FEM-Design Software for Building with RC and CLT Floors

The obtained results for the RC floors with the thickness of 250 mm from calculations following EC2 and the numerical analysis are compared in Table 3. The results are for primary bending reinforcements in the span and utilisation ratios in the primary x' direction.

Table 4 compares the obtained results for the CLT floors from calculations following EC5 and the numerical study. The calculations were performed on the utilisation ratios for the bending stress in x' direction and shear stress of the CLT floors with the thickness of 300 mm.

As can be witnessed from Tables 3 and 4, the results achieved from the calculations on the basis of Eurocodes (EC2 and EC5) and the numerical investigations were very close to each other, which verified the good accuracy of the numerical investigations of this study.

**Table 3.** Comparison of results for RC floors based on EC2 and numerical investigation

Features	EC2	Numerical investigation
Bending moment	26.6 kNm/m	23.96 kNm/m
Required reinforcement	280 mm <sup>2</sup> /m	256 mm <sup>2</sup> /m
Applied reinforcement	524 mm <sup>2</sup> /m	524 mm <sup>2</sup> /m
Utilisation ratio of reinforcements	53%	49%

**Table 4.** Comparison of results for CLT floors based on EC5 and numerical investigations

Features	EC5 Utilisation ratio (%)	Numerical investigation Utilisation ratio (%)
Bending stress	30	28
Shear stress	49	53

## 4. Conclusions

This paper compared the CLT and RC floors in an existing building considering their load-bearing properties, to check if the RC floors can be replaced with the CLT floors having the same span and thickness. The research work was done by the use of the StruSoft FEM-Design software. It was revealed that the CLT floor with the thickness of 260 mm can replace the RC floor with the thickness of 250 mm adopting a few reinforcing solutions.

However, it was shown that the CLT floors with the thickness of 300 mm could carry the design loads without reinforcing having acceptable deflections. Regarding the stability control of the building, the building with both of the CLT and RC floors was stable. The CLT floors of the building turned out to be significantly lighter than the RC floors. By using the CLT floors in the building, loads on the load-bearing parts and foundations could drastically be reduced as the weight of the materials is a decisive factor. This issue can make a considerable difference to the stresses in the soil which in turn can reduce the costs in terms of the foundation work, transport, etc. Comparisons of the obtained results from the numerical investigation with those from the calculations based on EC2 and EC5 uncovered the good accuracy of the numerical results.

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