PEIKKO
WHITE PAPER

PERFORMANCE OF DELTABEAM® – CLT FLOORS IN HUMAN-INDUCED VIBRATION

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INTRODUCTION

As a superior Slim Floor beam, DELTABEAM® can provide high load capacity and optimize room height at the same time. While it is commonly known as a main supporter of precast concrete slabs, it has a great potential to also work with other types of slab structures. Quick and effortless installations, as well as inbuilt fire capacity, makes DELTABEAM® a popular and economical choice for almost any kind of building.

CLT offers high strength and structural simplicity, which is also needed for cost-effective buildings. In addition, there are several other benefits like quick installations, improved thermal performance and versatility of design [2].

While the floor system, which consists of steel composite beams and CLT slabs, has already taken a firm foothold in some Central European countries (e.g., Germany and Austria), there has also been an increasing demand elsewhere.

Even though a combination of steel composite beam and CLT floor slabs provides several benefits to different stakeholders, there are also question marks about the functionality of the generated solution. One significant issue regarding light intermediate floors in residential, public or office buildings is its performance in human-induced vibration due to walking excitation.

As a forerunner, Peikko aims to establish the use of DELTABEAM® - CLT floors with longer spans and well-functioning structural composition.

SPECIFICATION OF STRUCTURES

DELTABEAM® is a steel box beam, which is filled with concrete at the construction site and works as composite beam in the final phase. It is used as a primary girder of floors, able to support different type of slabs, made from different materials. DELTABEAM® and its parts are illustrated in **Figure 1**.

Cross-laminated timber (CLT) is one of the massive timber product representatives. It is a planar slab product typically composed from an uneven number of lamination layers, which consist of several finger-jointed and glued panels [1]. CLT floor slab is illustrated in **Figure 2**.

SIGNIFICANCE OF THE STUDY

Even though CLT slabs have high strength for load bearing, they have relatively short supply of stiffness and mass. This may lead to insufficient performance in vibration unless the span lengths of structures are limited.

In case the stiffness and/or mass of plain CLT slabs are found to be too low, both can be improved by combining the CLT with in-situ concrete layer and forming the composite slab. Connected structures, taking advantage of their composite interaction, have a lot greater stiffness than the same structures without any connection between them. It is known that many connections and materials are much stiffer under dynamic conditions than static conditions, due to small deformations.

This paper evaluates how common design criteria for human-induced vibration due to walking excitation could be fulfilled economically with different DELTABEAM® - CLT floor types. The paper should help a reader to make a decision about the most suitable solution for his/her purposes.

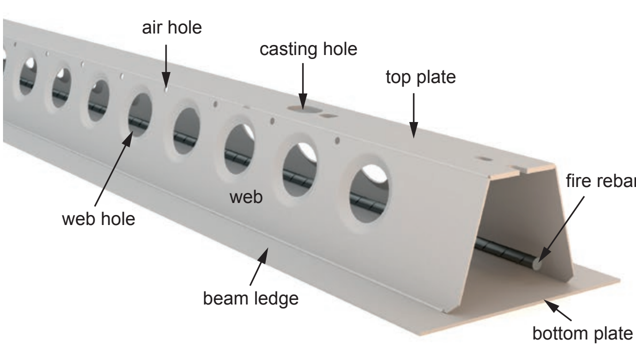


FIGURE 1 DELTABEAM® COMPOSITE BEAM AND ITS NOTABLE PARTS

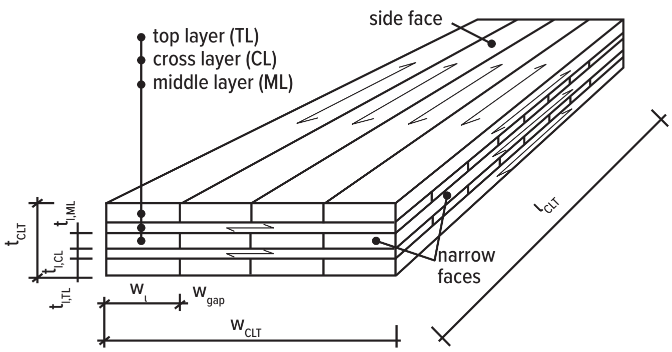


FIGURE 2 CLT FLOOR SLAB [1]

DESIGNATED DESIGN CRITERIA

There are two common ways to provide a criterion for limiting vibration. The first alternative is to limit the lowest frequency of the floor, which is considered as a simpler and more conservative approach. By restricting the lowest frequency to a certain limit, it is usually ensured that a resonance cannot occur from a periodical load component of the walking excitation (pace frequency around 1.6 – 2.2 Hz) and its second or third multiples. The second option, requiring more detailed study of the floor, is to limit the response caused by walking excitation. Response analysis is usually justified when the floor is known to be very sensitive to vibrations or fulfilling the criterion for the lowest frequency is found to be unviable.

Resonance is considered as a determining issue if the lowest frequency of the floor is less than 10 Hz. These floors are casually nominated as 'low-frequency floors'. Since CLT slabs supposedly have less stiffness and mass than concrete slabs, a limit for the lowest frequency is often given as high as 9 Hz. Such a high limit ensures that none of the first to the fourth periodical load components of the walking excitation will be intensified due to resonance phenomenon.

In practice, meeting the limit of 9 Hz with low-frequency floors may not be sensible from an economic point of view, especially if there is also a requirement for longer spans. As explained earlier, the lowest frequencies less than 9 Hz can still be acceptable if the actual response (e.g., acceleration) due to excitation is found to be satisfiable.

There are several publications suggesting the appropriate limits for the response of 'low-frequency floors'. One of the publications used in Finland is TRY 17/2005, Vibrations of floors due to walking excitation [3]. Another, more globally used source of the design criteria is SCI P354 Design of Floors for Vibration: A New Approach [4]. There, response limit is given as multiplying factors or Response factors R, calculated from root-mean-square values of accelerations.

In this paper, Response limit is chosen according to SCI P354 [4], since the study is performed with FE software, where the design approach of the same publication [4] is used. Recommended multiplying factor based on single person excitation for office floors is 8.

Both alternatives for limiting the vibration and their design criteria are concluded in **Table 1**.

Criterion	Limit
The lowest frequency, f	> 9 Hz
Response, R	< 8

TABLE 1 DESIGN CRITERIA

SPECIFICATION OF THE CASE STUDY

A benchmark is needed to assess how economically those two design criteria could be met with different DELTABEAM® - CLT floor types. It is provided by creating a case study with the following fixed parameters:

- Span length of DELTABEAM® 7m
- Span length of CLT slabs on both sides of DELTABEAM® 7m
- Width of one CLT element 3.5m
- Density of CLT slab 500 kg/m^3
- Constant critical damping ratio 0.03 (SCI P354, table 4.1)
- Imposed loads (in addition to self-weight of structures)
  - g2= 1.5 kN/m^2
  - q,k= 0.3 kN/m^2
- Pace frequency of the walker 1.6 – 2.2Hz
- Weight of the walker 80kg
- Hinged connection between the DELTABEAM® and the column
- Hinged connection for CLT slab end at exterior lines
- Continuity between the DELTABEAM® and the CLT slab
- Hinged connections between adjacent CLT slabs:
  - Discontinuity (free rotation) between plain CLT slabs
  - Only stiffness of concrete considered as secondary stiffness of composite slabs

MEETING THE DESIGN CRITERIA

Since loads, span lengths and other effective properties of the floor are fixed, the only way to influence results is by manipulating the mass and the stiffness. The goal is to find the most economical (the lightest) structure combinations that fulfils a chosen design criterion.

The study is executed with Finite Element software Robot Structural Analysis Professional 2016, where different CLT slabs are input as slab elements with constant thickness and material orthotropy and DELTABEAM® as beam elements with the material properties of structural steel (cross-sectional area and second moment of area inputs are scaled to take account the real cross-sectional properties of steel – concrete composite beam). Layout of the analysis model is presented in **Figure 3**. Model consists of 12 beams (red coloured) and 18 CLT slab elements. Primary load-bearing direction of CLT slab elements is presented with blue arrows.

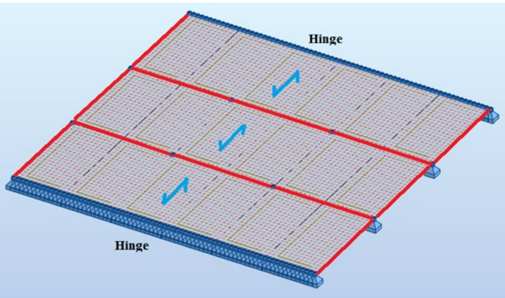


FIGURE 3 LAYOUT OF THE ANALYSIS MODEL

Performance is studied with the following DELTABEAM® and CLT sections, as well as their combinations.

- **DELTABEAM® profiles:** D20-400, D22-400, D26-400, D30-400, D32-400, D37-400, D40-500, D50-600
- **Plain CLT:** CLT 260 L7s-2, CLT 300 L8s-2, CLT 320 L8s-2
- **CLT + concrete topping:** CLT 120 L5s + 120mm, CLT 140 L5s + 120mm, CLT 180 L5s + 100mm, CLT 180 L5s + 120mm, CLT 200 L5s + 120mm, CLT 240 L7s-2 + 120mm, CLT 260 L7s-2 + 120mm

It has been individually verified that all chosen DELTABEAM® and CLT slab types perform at an acceptable level with the specs of the case study from the standpoint of load bearing (ULS) and deflections (SLS). All combinations between chosen slab and DELTABEAM® sections are also providing the lowest frequency higher than 4 Hz, which is commonly kept as a minimum requirement for vibration of the floors.

Examples about DELTABEAM® and CLT slab dimensions are presented in **Figures 4** and **5**.

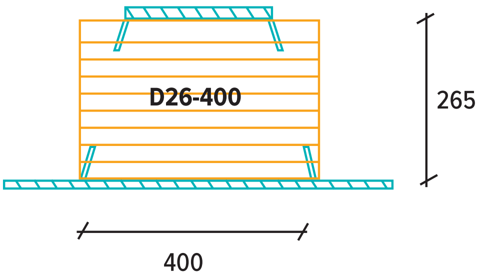


FIGURE 4 DELTABEAM® PROFILE DIMENSION EXAMPLES

I PLAIN CLT FOR LIMITING THE LOWEST FREQUENCY

Modal analysis, for defining the lowest frequency, is carried out with plain CLT slabs and DELTABEAM®. Considering only the listed beam and slab types, as well as their combinations, the lowest frequency with optimized structures is presented in **Figure 6**.

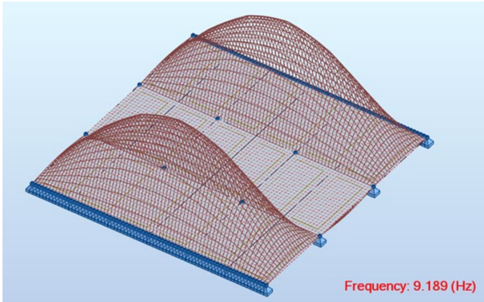


FIGURE 6 THE LOWEST FREQUENCY WITH OPTIMIZED STRUCTURES FROM CASE I

This is achieved by combining the plain CLT 320 L8s-2 slabs with DELTABEAM® D50-600. Mass and stiffness of both DELTABEAM® D50-600 and CLT 320 L8s-2 are shown in **Table 2**. Mass of DELTABEAM® also contains mass of the concrete casted inside.

Structure	Mass	Stiffness
DELTABEAM® D50-600	993 kg/m	432.8 MNm²
CLT 320 L8s-2	160 kg/m²	26.8[1]/3.3[2] MNm²/m

TABLE 2 MASS AND STIFFNESS OF THE CHOSEN STRUCTURES

[1]Bending stiffness about primary axis
[2]Bending stiffness about secondary axis

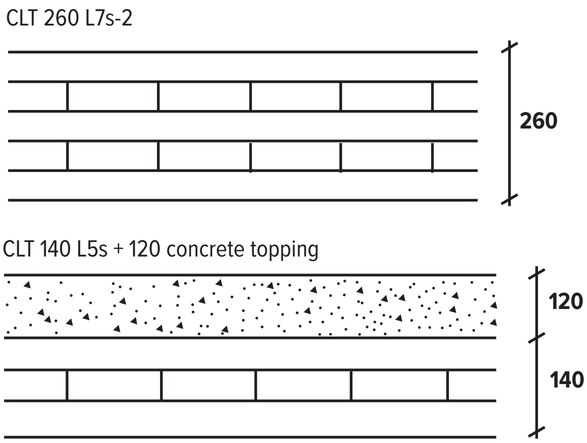


FIGURE 5 CLT SLAB DIMENSION EXAMPLES

II CLT + CONCRETE TOPPING COMPOSITE SLAB FOR LIMITING THE LOWEST FREQUENCY

Modal analysis is carried out with full-interaction composite slabs formed by CLT and topping concrete. Considering only the listed beam and slab types, as well as their combinations, the lowest frequency with optimized structures is presented in **Figure 7**.

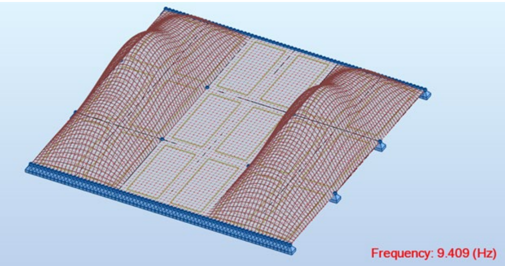


FIGURE 7 THE LOWEST FREQUENCY WITH OPTIMIZED STRUCTURES FROM CASE II

The lowest frequency presented in **Figure 7** is achieved by combining CLT 240 L7s-2 + 120mm concrete topping with DELTABEAM® D50-600. Mass and stiffness of both DELTABEAM® D50-600 and CLT 240 L7s-2 + 120mm concrete topping are shown in **Table 2**.

Structure	Mass	Stiffness
DELTABEAM® D50-600	993 kg/m	432.8 MNm²
CLT 240 L7s-2	120 kg/m²	70.8[1]/5.5[2] MNm²/m
120mm concrete	298 kg/m²	

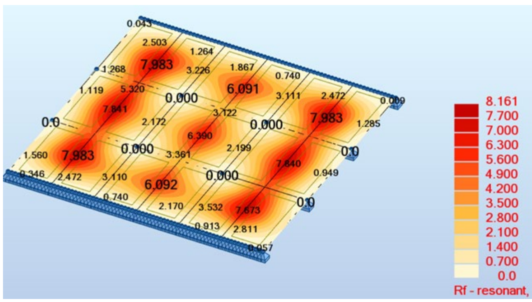
TABLE 3 MASS AND STIFFNESS OF THE CHOSEN STRUCTURES

[1]Bending stiffness about primary axis
[2]Bending stiffness about secondary axis

III PLAIN CLT FOR LIMITING THE RESPONSE

Footfall analysis, for defining the response due to walking excitation, is carried out with plain CLT slabs and DELTABEAM®. Response factors with optimized structures are presented in **Figure 8**. Now the maximum Response exceeds slightly the limit of 8, and it could be reached by using a bit thicker steel plates for optimized DELTABEAM® profile.

FIGURE 8 RESPONSE FACTORS WITH OPTIMIZED STRUCTURES



Values in Figure 8 are achieved by combining CLT 320 L8s-2 with DELTABEAM® D32-400. Mass and stiffness of both DELTABEAM® D32-400 and CLT 320 L8s-2 slabs are given in **Table 3**.

Structure	Mass	Stiffness
DELTABEAM® D32-400	492 kg/m	100.4 MNm²
CLT 320 L8s-2	160 kg/m²	26.8[1]/3.3[2] MNm²/m

TABLE 4 MASS AND STIFFNESS OF THE CHOSEN STRUCTURES

[1] Bending stiffness about primary axis
[2] Bending stiffness about secondary axis (stiffness of top concrete)

IV CLT + CONCRETE TOPPING COMPOSITE SLAB FOR LIMITING THE RESPONSE

Footfall analysis, for defining the response due to walking excitation, is carried out with full-interaction composite slabs formed by CLT and topping concrete. Response factors with optimized structures are presented in **Figure 9**.

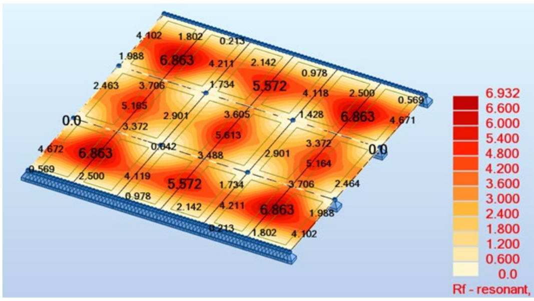


FIGURE 9 RESPONSE FACTORS WITH OPTIMIZED STRUCTURES

Values in **Figure 9** are achieved by combining CLT 120 L5s-2 + 120mm concrete topping with DELTABEAM® D20-400. Mass and stiffness of both DELTABEAM® D20-400 and CLT 120 L5s + 120mm concrete topping are shown in **Table 5**.

Structure	**Mass**	**Stiffness**
DELTABEAM® D20-400	346 kg/m	35.0 MNm²
CLT 120 L5s	60 kg/m²	20.2[1]/5.5[2] MNm²/m
120mm concrete	298 kg/m²	

TABLE 5 MASS AND STIFFNESS OF THE CHOSEN STRUCTURES

[1]Bending stiffness about primary axis
[2]Bending stiffness about secondary axis (stiffness of top concrete)

CONCLUSIONS

Exceeding the lowest frequency as high as 9 Hz requires both a significantly stiff DELTABEAM® profile and thick slab structure. Even though using plain CLT slab 320 L8s-2 leads to thinner floor thickness, estimated material costs are lower for composite slab CLT 240 L7s-2 + 120 mm (see **Figure 10**).

By neglecting the limit for the lowest frequency and concentrating on the response itself, many different beam – slab combinations can reach acceptable performance. Use of the composite structure formed by CLT and concrete topping is especially effective and has great potential to reduce the depth of the floor.

Optimized solutions for each case I – IV and their relative material costs for different floor structures are presented in Figure 10. The lowest cost (€/m^2) occurring from the combination of DELTABEAM® D20-400 and CLT 120 L5s + 120mm top concrete is benchmarked as 100% and used for comparing the costs of other structure combinations.

The study has shown that potential for creating not only well-functioning, but also cost-effective DELTABEAM® - CLT floors does exist. However, the acceptability of such floors must always be assessed case by case: appropriate design criterion, must be picked using a related design method based on the use of the floor and the choice governed by a client.

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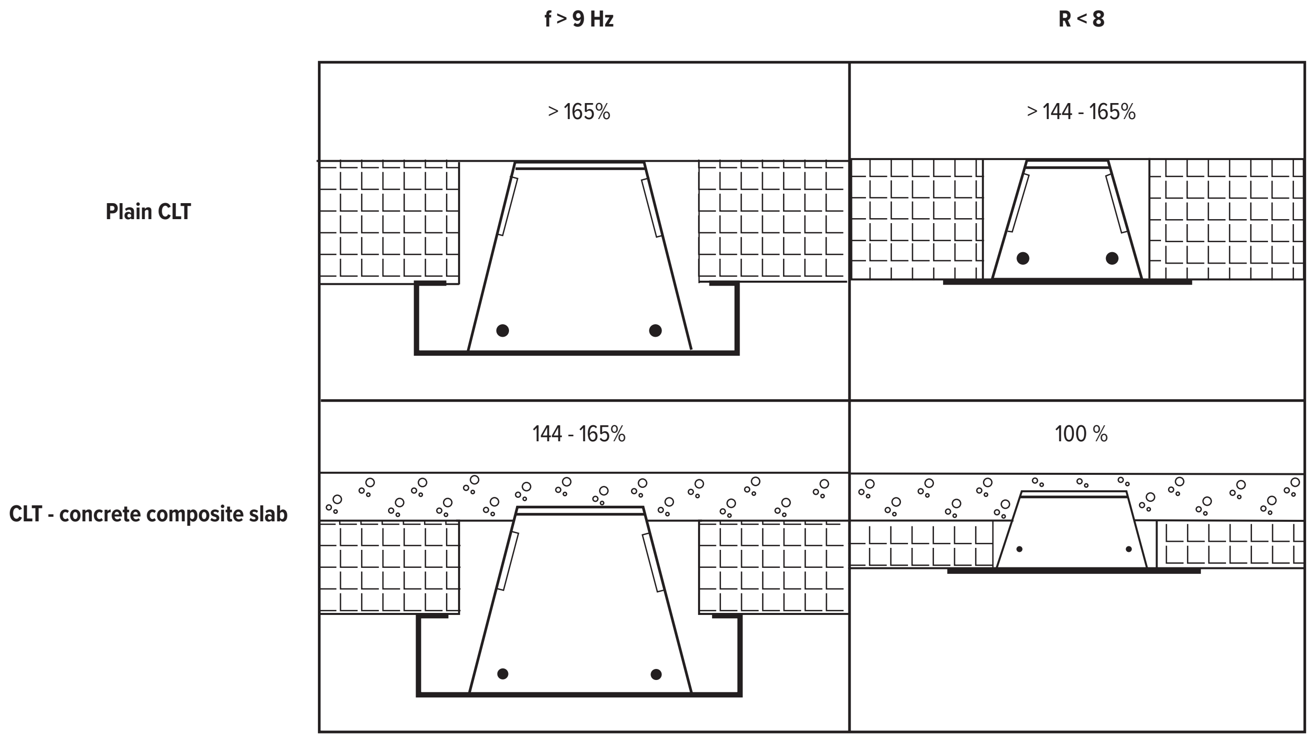

FIGURE 10 SCHEMATIC PRESENTATION OF DIFFERENT OPTIMIZED APPLICATIONS BASED ON CHOSEN DESIGN CRITERION


DELTABEAM

A faster, safer, and more efficient way to design and build