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Suitability of slim-floor steel-timber composites as intermediate floor constructions - case study based on projects in Finland

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ABSTRACT: The structural engineer provides module divisions and intermediate floor structural thicknesses for the preliminary architectural design. Usually, such data is based on design guidelines provided by manufacturers, national design guides or experiential knowledge from earlier projects. However, there are a few well-known and standardized timber floor systems in Finland, and the knowledge of timber composite structures is still very limited, largely because of the small number of reference cases. Therefore, this study addresses the gap by first presenting general information regarding the slim-floor steel-timber composite (slim-STC) and timber-concrete composite (TCC) systems. Furthermore, this study analyses the implementation of the slim-STC system in the existing office and public buildings in Finland by comparing the vibration behaviour of the slim-STC floor to the selected reference cases. The used six reference cases were selected from Sweco Finland Oy projects and they are representing the typical timber floors and TCC solutions used in office and public buildings in Finland. Based on the analysis, the slim-STC system can provide advantages to the vibration behaviour and the structure could be successfully used in office and public buildings in Finland without complex technical barriers because it has many similarities with the existing floor solutions.

KEYWORDS: Steel-timber composite, Intermediate floor, timber construction

1 INTRODUCTION

New timber-based composite floor structures, such as timber-concrete composite (TCC) and steel-timber composite (STC) floors, have been shown to provide material efficiency and higher load-bearing capabilities by utilizing the best aspects of the used materials (Aspila et al. 2022, Hassanieh et al. 2017a, Heinisuo et al. 2019, Karki and Far 2021, Karki et al. 2021, Loss and Davison 2017, Lukaszewska 2009, Siddika et al. 2021). However, to utilize these new composite structures, information about their capabilities and design methods needs to reach all the stakeholders involved in construction projects. For example, the structural designer should provide module divisions and structural thicknesses for the architects in a relatively early stage of the project to avoid project delays and additional expenses arising from necessary design changes. Usually, such data is based on experience or can be found in design guidelines provided by manufacturers and national regulations. In the project's later phases, the structural design becomes more precise and detailed, and the structural designer needs relevant design rules and calculation tools for validating the selected structural solution. In Finland, the properties of STC and TCC floors are not well-known, and the number of reference cases is still small. Thus, providing information regarding these solutions is more time-consuming and challenging when compared to more traditional floor structures like plain timber or concrete floors.

This study provides information to various parties involved in public and office building projects by first discussing the most important structural design aspects and challenges in intermediate timber or timber composite floor structures when using a beam-column frame system. Secondly, general information about the STC and the TCC systems is presented, based on the literature, so that the advantages and disadvantages of these solutions would be better known. The paper pays special attention to a slim-floor STC floor configuration called the Nordic System. Finally, a comparative analysis is conducted by studying the feasibility of the slim-floor STC solution in selected realized reference cases. The reference cases are provided by Sweco Finland Oy, and they include typical timber floor solutions used in office and public buildings in Finland. The presented information is summarised and the suitability of the slim-floor STC system is discussed for the Finnish public and office building projects.

2 STRUCTURAL DESIGN ASPECTS

2.1 Critical design criteria

The design of timber floor structures consists of two parts - the ultimate limit state (ULS) and the serviceability limit state (SLS) considering structural safety, and user comfortability issues, respectively. The dimensions of timber floors are determined by the SLS design criteria for vibration and maximum deflection especially when using long span (Fink et al. 2018a). The wood material itself has a relatively high stiffness-to-weight ratio, which results in high flexural vibration frequencies. However, the acoustic and fire resistance properties of the wood, as well as the associated regulations require additional structural layers, which in turn inevitably degrade the timber floor vibration properties. Hence, getting the intermediate floor's lowest natural frequency above the threshold value (9 Hz in Finland) sets the most demanding condition for the floor design. Reaching this threshold becomes a harder task if the timber floors are supported by flexural beams affecting the combined vibration.

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In the ULS design, the most critical design criterion is typically the perpendicular compressive strength in the support or load areas. Additionally, in cross-laminated timber (CLT) floors, the rolling shear strength is another key criterion. These strength criteria are such, that exceeding the associated limit value does not lead to an overall collapse of the floor structure, but instead to local damages. Thus, from the structural design perspective, the SLS design criteria for vibration and deflection are the most significant ones. Consequently, the bending stiffness of the floor can be stated as the most important design parameter as it affects both criteria. Bending stiffness can be affected by modifying the following properties: floor supporting structures and boundary conditions, floor material stiffnesses, and floor cross-section shape and dimensions. As the possibilities to modify the abovementioned features in pure timber floors are rather limited, the STC and TCC become very attractive choices for intermediate floor structures.

The current Eurocode 5 (CEN 2005) provides design guidance only for timber floors that consist of glued or mechanically jointed beams and timber decking whereas similar international guidance is not provided for CLT and STC floors. The lack of guidelines for these structures has been identified as a barrier that hinders the mainstreaming and structural understanding of these solutions (Cheraghi-Shirazi et al. 2022, Fink et al. 2018b, Schenk et al. 2022) According to Schenk et al. (2022) "different tools, based on different background theories and with different levels of accuracy may lead to quite diverging results." Considering the TCC floors, additional guidance to the Eurocode 5 was given in 2021 where the ULS design is presented but no further guidance regarding SLS is given (CEN 2021). The SLS deign for TCC is described by Cuerrier-Auclair (2020), Breneman et al. (2021).

2.2 Determining the key structural responses

As justified above, the vibration and deflection properties are the most significant ones when examining the feasibility of the floors to be applied in different construction projects. In what follows only the vibration properties are considered in more depth in terms of the design equations for the floor's lowest natural frequency. The design criterion for the deflection is more straightforward to calculate requiring mainly relevant methods for considering the partial composite action as presented eg. in (Aspila et al. 2022).

The lowest natural frequency of a one-span timber floor supported by rigid supports, for example by walls, can be modelled as a beam and calculated, according to Eurocode 5 as

$$f_0 = \frac{\pi}{2L^2}\sqrt{\frac{EI_L}{m+m_1}} \qquad (1)$$

where L is the span length of the slab, EI_L is the bending stiffness along the span length, m is the structural mass per unit length and m_1 is an additional 30 kg/m mass, that considers the live loads according to the Finland's national Annex. In the upcoming Eurocode 5 the m_1 is 10 % of living load (CEN unpublished (updated 2022-05-30)).

Equation (1) assume that the supports underneath the floor slabs are rigid, which is not true in the case of STC floors. Thus, the combined vibration of the floor slab and the supporting steel beam must be both considered. Typically, such a combined vibration problem for a floor slab supported by two flexible beams can be analysed by using the Dunkerley relation as

$$f_{sys} = \sqrt{\frac{1}{\frac{1}{2*f_{0.beam,1}^2}+\frac{1}{2*f_{0.beam,2}^2}+\frac{1}{f_{slab}^2}}} \qquad (2)$$

in which the subscript *slab* stands for the floor slab, the frequency of which can be calculated according to Equation (1). The subscripts *beam,1* and *beam,2* denote the steel beams that are supporting the slab. In the calculation of the term $f_{0,\mathrm{beam}}$ for STC structures, the composite action between the timber slab and the steel beam can be taken into account by using eg. the layered beam theory as shown by Aspila et al. (2022). It should be noted that the upcoming Eurocode 5 proposes changes to equation (2) in a form

$$f_{sys} = \sqrt{\frac{1}{\frac{1}{3*f_{0.beam,1}^2}+\frac{1}{3*f_{0.beam,2}^2}+\frac{1}{f_{slab}^2}}} \qquad (3)$$

in which the influence of the supporting beam frequencies is reduced.

3 TIMBER-BASED COMPOSITE FLOORS

3.1 The composite action

Timber-based composite structures can provide lightweight structures, quick installation, and low greenhouse emissions as well as increased structural capacity to carry loads and floor spans. Nowadays there exist two main systems for timber-based composite floors, STC and TCC. In STC the composite action is formed with a steel beam by using bolts and screws as shear connectors. In the case of TCC the composite action is formed with a concrete slab by using not only dowel-type shear connectors but also grooving in the timber slabs. The structural behaviour of composite structures is determined by the degree of the composite action, which can be separated into three different stages as shown in Figure *1*.

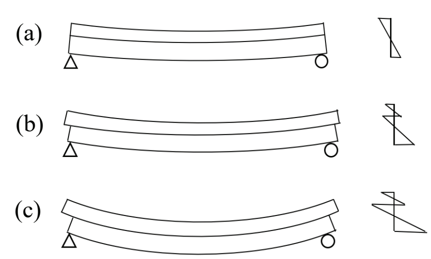

Figure 1. *Deflections and bending stress with different degrees of composite action, (a) full, (b) partial, and (c) no composite action at all.*

The first stage is full composite action where the two parts are acting as one solid block of material and there is no slip between different parts. The second stage is partial composite action in which the flexibility of the connections causes a slip between the parts. Lastly, if the connection is so weak that it does not carry the shear force at all, the slip is free to occur, and no composite action is formed. Thus, the degree of the composite action is governed by the stiffness and load-carrying capability of the connection.

The effectiveness of the composite action is governed by the distance between the centroids of the beam and slab as depicted in Figure 2. Increasing the distance also increases the effectiveness of the composite action providing that the connectors can carry the increased shear forces between the parts.

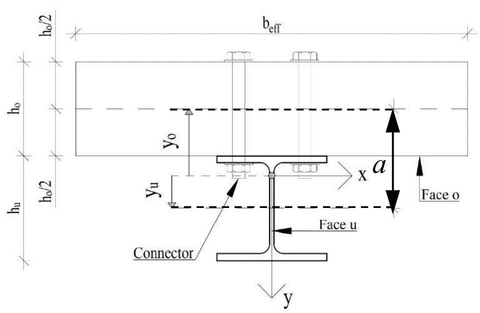

Figure 2. *Cross-section of a traditional STC. The parameter a denotes the distance between part centroids.*

3.2 TIMBER-CONCRETE COMPOSITE FLOORS

The concrete slab has traditionally been used as a reinforcing layer on top of the wooden slab to improve the fire and acoustic properties of the floor. By forming a composite action between timber and concrete parts, structural efficiency, load-bearing capacity, and vibration performance can be substantially increased (Cuerrier-Auclair 2020, Lei Zhang 2022, Siddika et al. 2021). In Finland, TCC structure is typically constructed by using CLT slabs beneath the concrete slab as illustrated in Figure 3. In such a configuration, the CLT slab also provides the casting mould and the support during the construction. The composite action is formed by using screws and grooves.

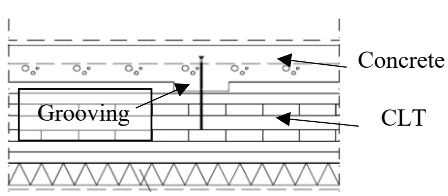

Figure 3. *Typical Finnish CLT-concrete slab has a total height of ca. 200 mm CLT and 100 mm concrete. Due to the fire and the impact of sound insulation regulations, linings might be needed above or below.*

ULS of TCC structures can be analysed by using the Eurocode 5 design guides (CEN 2021). In general, the TCC floors are considered robust structures, in which the only feature requiring further research, is the long-term deflection determination affected by different creep properties of concrete and timber (Breneman et al. 2021).

3.3 STEEL-TIMBER COMPOSITE FLOORS

Steel-timber composite floors differ from the TCC floors substantially since the composite connection is formed now between a slab and a beam, not between two slabs. Depending on the location of the steel beam, the STCs can be divided into two categories. In traditional STC floors the steel beam is located beneath the slab as shown in Figure *2*, whereas, in slim floors, the timber slab is supported by the lower flange of the steel beam as shown in Figure 4. In traditional floors, the efficiency of composite action can be high because the centroids of the beam and the slab are far from each other, as pinpointed in Figure *2*. Typically, such STC structures produce 30%-90% higher load-bearing capacities compared to non-composite constructions (Aspila et al. 2022, Hassanieh et al. 2017b, Karki et al. 2021, Loss and Davison 2017). However, the connections between the steel beam and timber slab must be capable of carrying the developed high shear forces and the connections must be stiff enough to form the desired degree of the composite action. The importance of the connections has led to intense research and development of different connection types such as (Chybinski and Polus 2022, Hassanieh et al. 2017b, Hassanieh et al. 2017c, Loss et al. 2016a, Loss et al. 2016b, Yang et al. 2020).

Field Heinisuo et al. (2019) present the slim-floor STC concept where the possibilities of slim-floor steel-timber composite structures are discussed. The most important benefit of the slim-floor application is the reduced total floor height which in turn creates material savings on the vertical structures and allows the building of more floors with the same building height.

In this paper, the considered slim-floor STC, called as a Nordic system, consists of CLT slabs connected to the welded WQ-beam as presented in Figure 4. In this system, the composite connection is formed by using steel plates on top of the WQ beam and the CLT slab. All the installation regarding the connections can be carried out on top of the platform and the connections can be also easily disassembled. As in all slim-floor configurations, the effectiveness of the composite action is rather small, but based on the results given by Heinisuo et al. (2019), the composite action can reduce the stresses in the steel profile by up to 20%.

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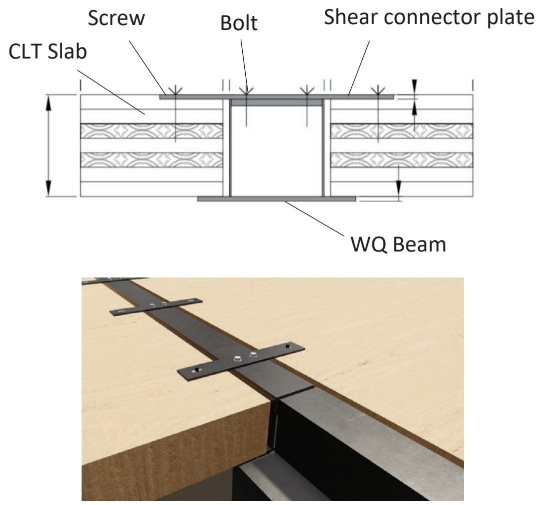

__Figure 4.__ The considered Nordic system slim-floor. Cross-section (top) and side-view (bottom). The CLT slab and the steel beam are fastened only on top of the profile using the steel plates.

4 COMPARATIVE ANALYSIS

4.1 Reference cases

The practical feasibility of the Nordic system in the office and public buildings is studied by comparing the key structural responses in realized construction projects. The reference cases are chosen from timber construction projects conducted or participated in by Sweco Finland Oy. A total of two schools and six office building projects with the beam-column system were selected. In the selected reference cases the intermediate floors were built by using TCC, CLT or LVL ribbed-slab systems, see Table 1. Figure 5 illustrates the platforms with modulus divisions.

Table 1. *Reference case data.*

Reference cases						
Floor				*Primary beam*		
Case	Type	Code	Span (m)	Type	Code	Span (m)
1	TCC	220mm 60-30-40-30-60 100mm C37/45	7,0	GL30c	240x1080	7,0
2	CLT	160mm 40-20-40-20-40	4,0	Delta	D40-500-20	7,0
3	LVL-ripa	H661-5x63x600	8,5	LVL-X	225x590 300x590 (midle)	4,8
4	TCC	220mm 60-30-40-30-60 80mm C30/37	6,0	Delta	D32-400	6,0
5	CLT	280mm 80-40-40-40-80	6,0	LVL-X	2x288x890	6,7
6	TCC	220mm 80-40-40-40-80 80mm C30/37	5,5	WQ22-500	260x20- 2x6x200- 20x500	5,3

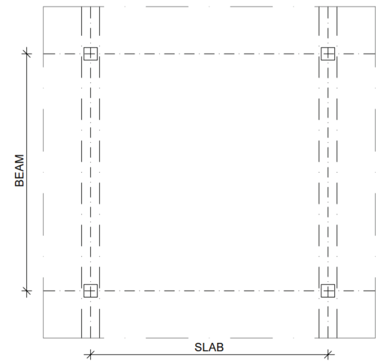

Figure 5. *Platform and modulus divisions of reference cases.*

Table 2 presents the design parameters such as the top and bottom surface masses, self-weight of the structure and living load for the reference cases.

Table 2. *Reference case design parameters.*

Reference cases				
Design parameters				
Case	Top surface mass (kg/m2)	Bottom surface mass (kg/m2)	Selfweight (kN/m2)	Living load (kN/m2)
1	10,0	4,0	3,8	5,0
2	37,0	3,0	0,7	2,5
3	74,0	30,0	0,4	3,0
4	50,0	14,0	3,2	2,5
5	90,0	14,0	1,2	3,8
6	69,0	14,0	3,2	5,0

4.2 Calculation of the Nordic system

The Nordic system is calculated by using the presented data from the reference cases. Span lengths and living loads are taken directly from Table 1 and Table 2. However, for cases 1, 3, 4 and 6 the medium of cases 2 and 5 values were used, see Table 3. For each case, the extra load imposed by the heating, ventilation, and air conditioning (HVAC) was taken also into consideration as a permanent load.

Table 3. *Design loads used to calculate the Nordic system.*

Nordic system				
Design parameters				
Case	Top surface mass (kg/m2)	Bottom surface mass (kg/m2)	HVAC load (kN/m2)	Living load (kN/m2)
1	63,5	8,5	0,5	5,0
2	37,0	3,0	0,5	2,5
3	63,5	8,5	0,5	3,0
4	63,5	8,5	0,5	2,5
5	90,0	14,0	0,5	3,8
6	63,5	8,5	0,5	5,0

The results of the calculation are presented in Table 4 where presented values are obtained by calculating CLT as a beam structure by using Equation (1). In Table 4 the f_1 refers to the lowest natural frequency of the floor

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structure that was calculated by using Equation (1) and f_2 refers to the lowest natural frequency of the floor systems that can be calculated by using Equation (2) or (3). Results were obtained by optimizing the CLT and WQ-beam to reach the 9,0 Hz frequency according to the upcoming Eurocode 5.

Table 4. *Nordic system midfloor solution where CLT is calculated as a beam structure.*

Nordic system, CLT as a beam								
	Beam		*floor*		*EC5*		*Upcoming EC5*	
Case	WQ-type	Weight (kg/m)	CLT -type	Weight (kg/m)	f1 (Hz)	f2 (Hz)	f1 (Hz)	f2 (Hz)
1	470x6-360x15-572x13	145,0	320mm 80-40-80-40-80	134,4	9,2	6,7	8,9	7,2
2	330x6-260x15-472x12	106,2	180mm 40-30-40-30-40	75,6	13,8	7,9	14,0	9,1
3	570x8-450x20-662x15	220,2	320mm 80-40-80-40-80	134,4	6,3	6,3	6,3	6,2
4	400x6-370x20-582x15	164,3	300mm 80-40-60-40-80	126,0	10,7	8,4	10,8	9,1
5	570x8-400x20-612x14	201,7	320mm 80-40-80-40-80	134,4	10,6	8,6	10,5	9,0
6	280x6-350x15-562x12	120,5	280mm 80-40-40-40-80	117,6	12,4	8,3	11,9	9,0

4.3 Comparison

The conducted calculation allows comparison between the Nordic system and reference cases as well as between current Eurocode 5 and upcoming Eurocode 5. A comparison between the Nordic system and reference cases is presented in Table 5. Cases 1 and 3 did not reach the boundary limit value of 9 Hz when CLT was calculated as a slab.

Table 5. *Comparing the structural height of the Nordic system to the reference cases when CLT is calculated as a beam structure.*

Comparing Nordic system structural heights to reference cases						
	Reference cases		Nordic system		Comparison	
Case	Floor	Floor+beam	CLT as a beam	CLT+WQ	Floor difference	Floor+slab difference
1	320,0	1400,0	-	-	-	-
2	160,0	400,0	180,0	330,0	-11 %	21 %
3	661,0	1251,0	-	-	-	-
4	300,0	320,0	300,0	400,0	0 %	-20 %
5	280,0	1170,0	320,0	570,0	-13 %	105 %
6	300,0	300,0	280,0	280,0	7 %	7 %

A comparison between the current and the upcoming Eurocode 5 has been shown in Table 6. Upcoming Eurocode 5 provides better values in all cases when examining the lowest natural frequency of the floor system.

Table 6. *Comparing results from Table 4 where the lowest natural frequencies are calculated according to Eurocode 5 and upcoming Eurocode 5.*

Comparing Eurocode 5 and upcoming Eurocode 5		
	CLT as a beam	
Case	f1 (Hz)	f2 (Hz)
1	-3 %	7 %
2	1 %	15 %
3	-2 %	-2 %
4	1 %	8 %
5	-1 %	5 %
6	-4 %	8 %

5 DISCUSSION AND CONCLUSION

This study presents some key design aspects in timber and timber-composite floors in the context of the beam-column structural system. Special attention is paid to a steel-timber composite slim-floor system called the Nordic system. The major objective of the study is to examine the feasibility and effectiveness of the Nordic system in typical practical applications in office and public construction projects in Finland. Based on a selected set of realized construction projects, the results prove that the Nordic system would result in slimmer solutions compared to the adopted current floor types by offering a total build-to-be-disabled floor system. To adopt the full potential of the studied slim-floor system, further research should be carried out to accurately determine the slabs' effective width and formulate an overall structural optimization design task for the whole floor system where the bending stiffness of the CLT in both directions should be taken into consideration.

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