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COMPARATIVE ANALYSIS OF COMPOSITE TIMBER-CONCRETE CEILING SYSTEMS

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ABSTRACT

This paper compares two concepts of composite timber concrete ceilings and their uncoupled alternatives based on a parametric study by comparing the final deflections of individual variants and at the same time considering according to the ultimate limit state. It includes a comparison of coupled and uncoupled variants while maintaining the same boundary conditions as the load, the thickness of the ceiling structure and the load width. By considering other factors, we can achieve more optimal variant, thanks to more accurate consideration of the required boundary conditions such as the complexity of installation or fire resistance. The purpose of this paper is to simplify the optimal selection of the ceiling structure based on the suitability of the supporting structure.

KEYWORDS: Composite structure, ceiling, cross laminated timber, timber, shear connectors.

INTRODUCTION

At present, the accent is on the usage of materials and structures that leave as little carbon footprint as is possible. As is widely known, wood is the most suitable basic construction material. As part of wood-based material is CLT too. CLT is relatively new material, it was developed just at the end of 20^{th} century (Brandner et al. 2016). It is commonly applied as structure member as ceilings or walls in multi storey buildings or structures with requires longer span like congress halls, galleries, or schools (Ceccotti 2002). High material resistance compared to the weight is main benefit in elements like CLT panels. Each segment consists of three-, five- to seven- layers of lamellas. Each layer is applied perpendicular to layer before (Aicher et al. 2001). It is rule, that outer layers must be in the same way as main load capacity (Bajzecerova et al. 2018). In some cases, CLT panels as ceilings may be insufficient. To use most of the potential of these structures, it is necessary to apply shear connectors. It is well known that by applying a coupling, the ceilings can be more effective by coupling appropriate materials and components, e.g., timber beam with concrete deck (Surovec and

Slivanský 2015). Coupling ensures the interaction of individual materials and increases the load-bearing capacity and rigidity of the structure (Jiang and Crocetti 2019).

By creating a composite cross-section, it can be ensured the interaction of two elements (Fig. 1) (Ahmed and Tsavdaridis 2019). This phenomenon can be verified based on the course of normal stresses along the height of the cross-section (Lukaszewska et al. 2008).

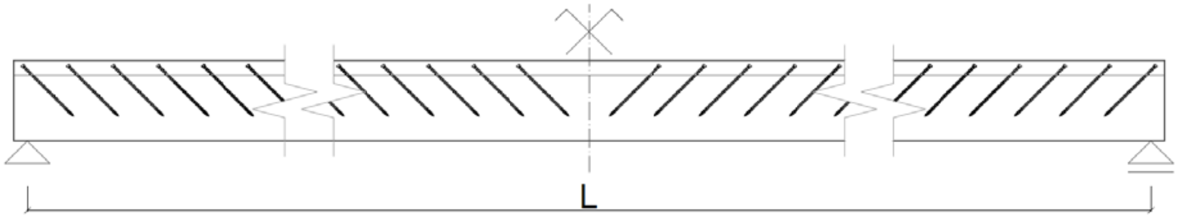

Fig. 1: Longitudinal section of the location of the coupling by self-tapping screws.

In the context of this study, it is specifically the interconnection between timber and concrete elements. To secure the coupling, it is possible to use mechanical coupling by self-tapping screws as well as grooving (Čajka and Burkovič 2013) (Mai et al. 2018), notched conectors (Yuchen and Crocetti 2019) (Loebus et al. 2017) or gluing. The study is aimed on the usage of screws that belong to the category of flexible mechanical shear connectors, especially: Rotho Blaas CTC 9 mm thickness at 240 mm (Rotho Blaas GmbH, 2021: Screws and connectors for timber 2021). The screws are applied at an angle of 45°.

MATERIAL AND METHODS

Composite beam timber-concrete ceiling

At the bottom of the cross-section are used timber beams as construction beams (T) of strength class C24. The cross-sectional dimensions are varied and compared in study. Width (W_T) of beams in this study is used the same, namely 120 mm. A cement-chipboard of constant thickness of 28 mm is used for the formwork. The concrete layer, which is used as part of the composite cross-section, is designed to have a constant thickness (H_{con}) of 50 mm with one row of reinforcement that is used only to avoid excessive confusion of the concrete (EN 1992-1-1, 2004). The same load width of 1m is used in this variant. The effective width is identical to the load width (Fig. 2).

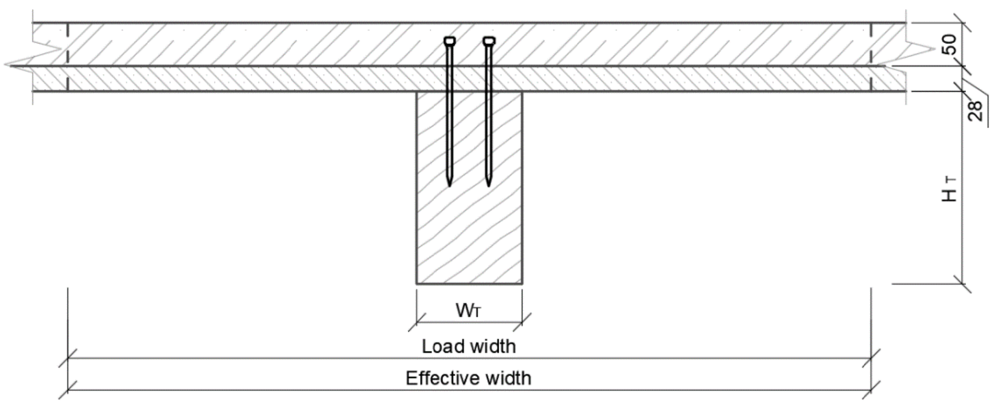

Fig. 2: Cross-section of composite beam timber-concrete ceiling.

Composite slab timber-concrete ceiling

Solid timber panel from cross laminated timber (CLT) is used as part of a coupled cross-section and provides a support function and further replaces the need to use formwork (Fig. 3). The study uses panels intended for application to ceiling structures, which means that the outer layers of the CLT panel are in the longer direction of the slab and at the same time in its direction with higher load-bearing capacity. The thickness and number of layers varies based on the needs of the study. Since it is a slab element, the load width refers to 1m. As it is in previous variant, load width and effective width are equal. Concrete of the same strength class C20/25 of constant thickness with one row of reinforcement is used as another material in the composite ceiling.

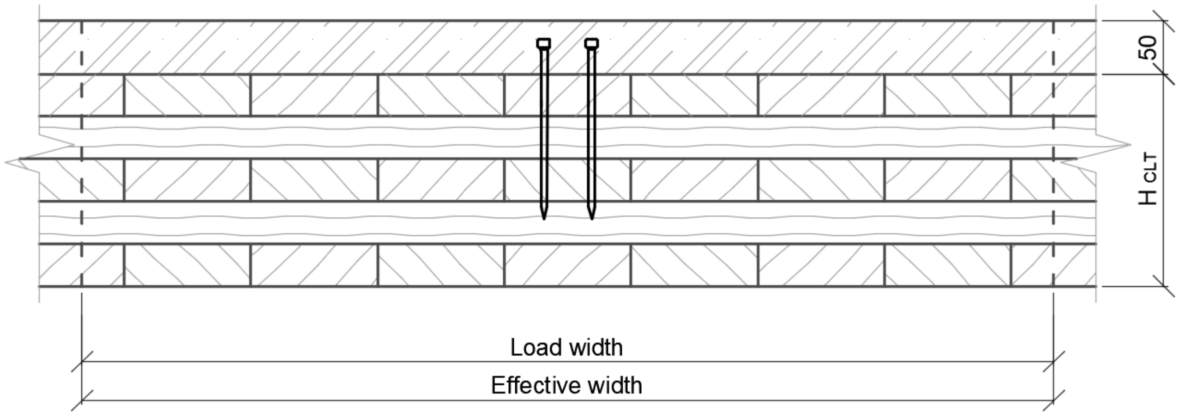

Fig. 3: Cross-section of composite slab timber-concrete ceiling.

Non-composite variants of timber-concrete ceiling

For verification efficiency of coupling were created non-composite variants. To verify the effectiveness of the coupling, uncoupled variants were created. In both cases, the coupling by self-tapping screws were not applied, the following boundary conditions were maintained as in the previous variants.

Test set-up

The analytical study is prepared in the MS Excel program. Algorithm consists of different material parameters and geometric parameters. In the calculation is necessary to account differences between used cross-sections. Used variants have equal values of surface loads consisting of imposed load (2 $kN\cdot m^{-1}$), and predefined loads as load from load-bearing and non-load-bearing walls (2,78 $kN\cdot m^{-1}$), and load of layers of floor (1,2 $kN\cdot m^{-1}$) expect for self-weight load. These values changes based on the change in the thickness and density of used wood-based material (EN 1991-1-1, 2002). In first step, the γ-method is necessary to apply in the variant with CLT panel (EN 1995-1-1, 2004). Based on this method, it is possible to take into the account the efficiency of individual layers and express the corresponding moment of inertia of the effective cross-section of the CLT segment. Subsequently, the method of idealized cross-section is applied, which is based on the creation of an idealized cross-section originally consisting of several materials. This result can be achieved after calculating with the partial coefficient, it is used to obtain effective cross-sectional characteristics specified in the EN 1995-1-1 Annex B. Method is valid for combination as for CLT and concrete as timber-beam concrete structure.

The sample is assessed as part of the analysis in the first step. The cross-section is assessed for the ultimate limit state (ULS) for various stress methods along the height of the cross-section. The instant deflection is count for serviceability limit state (SLS). In the next step is count is offset further for SLS and ULS at the end of life are evaluated (EN 1991-1-1, 2002).

RESULTS AND DISCUSSION

Comparison of efficiency of support systems

Numbers of factors affect the effectiveness of a design e.g., type of material and geometrical parameters, quantity and type of shear connectors, load width and effective span of the ceiling structure (Dias et al. 2015).

Deflection is one of the factors that determines the ability to use. Exceeding the values does not say that the structure collapses, it expresses comfort and the possibility of use. Excessive curvature of roof can cause some devices to malfunction (Ataei et al. 2019).

Since deflection also corresponds to the time. Due to the effect of time, the joints are loosened, and these results are an increase in the already instant deflection and thus the final deflection created (Hassanieh et al. 2017, Kanócz and Bajzecerová 2012, Khorsandnia et al. 2015). By comparing instant deflection in Figs. 4-7 and final deflection in Figs. 8-11 it can be seen increase in deformation. This has the effect of reducing the scope of the use of span.

Also, it is known that the thickness of the structure affects the final deflection of the structure. The effect of improving parameters of ceiling can be seen gradually in Figs. 4-7. It is shown that the coupled slab ceiling is more effective and can be applied to a range of approximately 9.5 m. On the other hand, a beam-coupled ceiling can only be applied up to a span of approximately 6.5 m with a load width of 1 m. Coupled variants are more efficient as uncoupled variants and is possible to overcome a longer span.

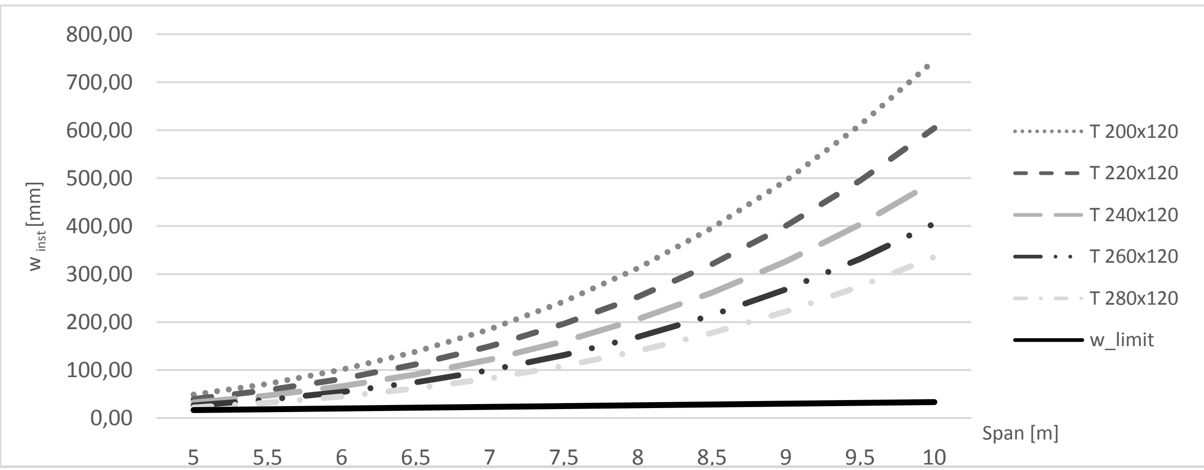

Fig. 4: Comparison of instant deflection depending on thickness of noncoupled beam-concrete and length of span.

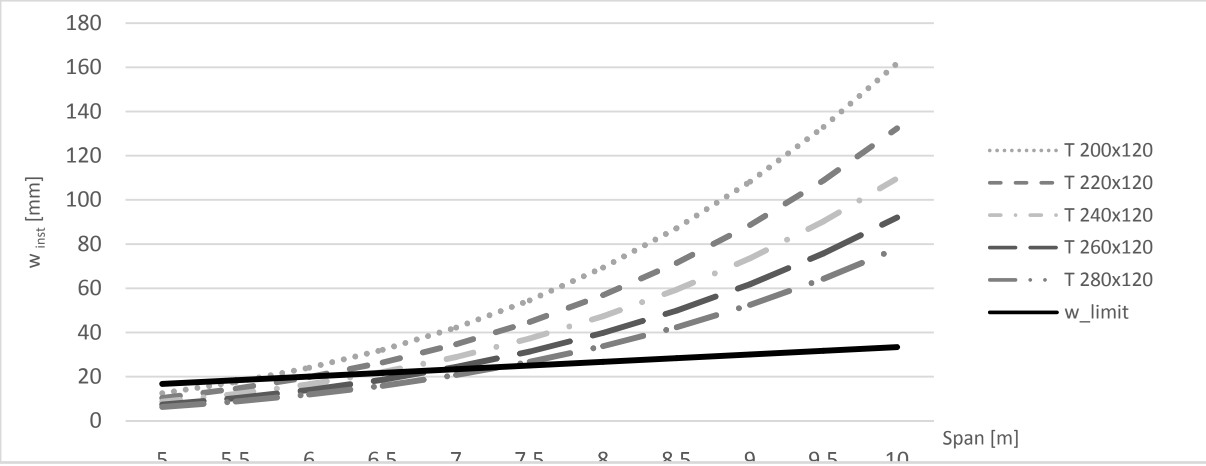

Fig. 5: Comparison of instant deflection depending on thickness of coupled beam-concrete and length of span.

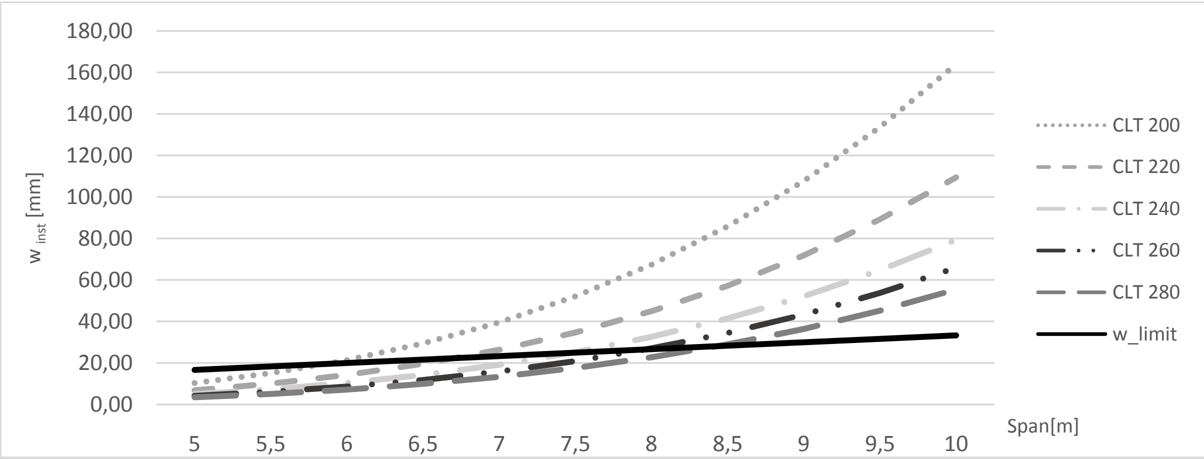

Fig. 6: Comparison of instant deflection depending on thickness of noncoupled CPT-concrete and length of span.

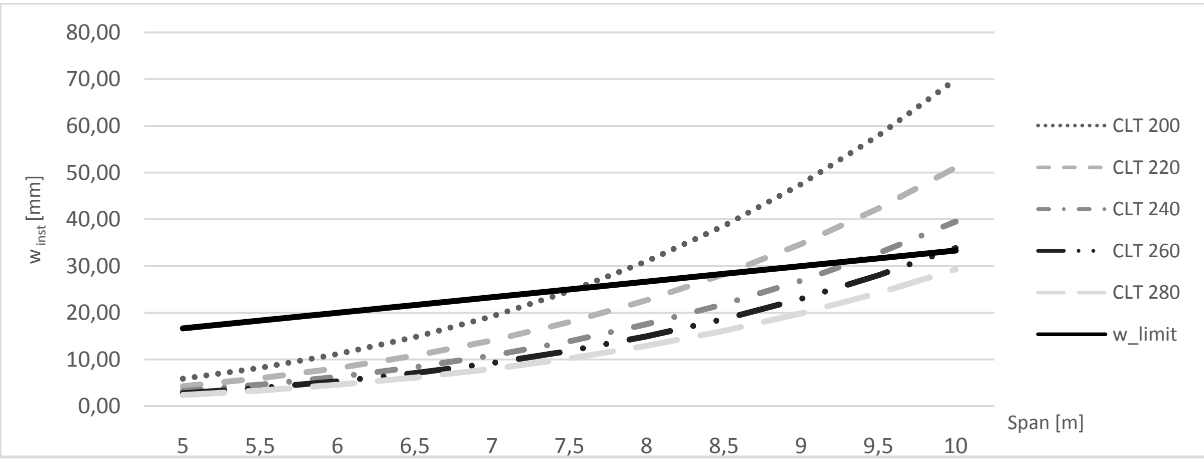

Fig. 7: Comparison of instant deflection depending on thickness of coupled CLT-concrete and length of span.

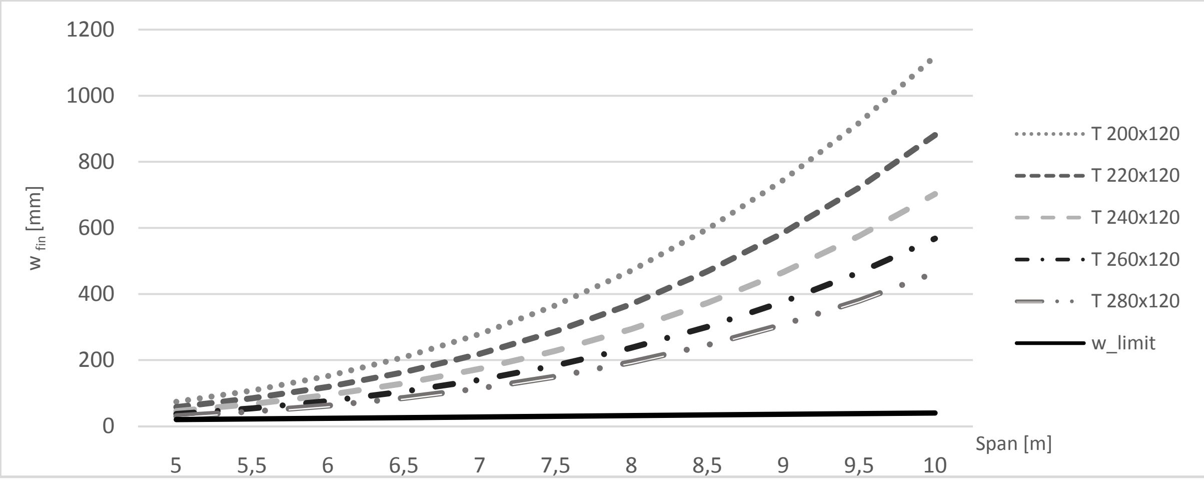

Fig. 8: Comparison of final deflection depending on thickness of noncoupled beam-concrete and length of span.

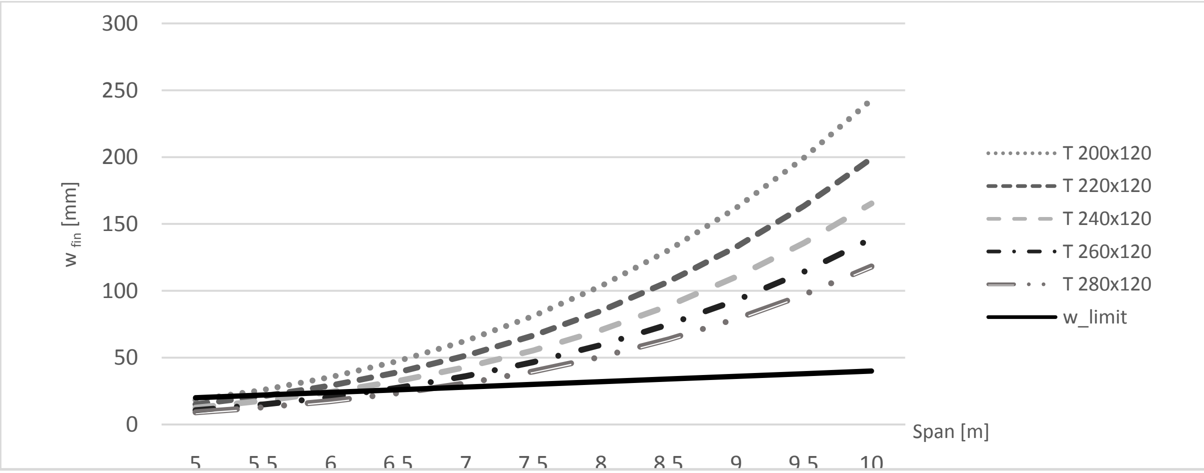

Fig. 9: Comparison of final deflection depending on thickness of coupled bean-concrete and length of span.

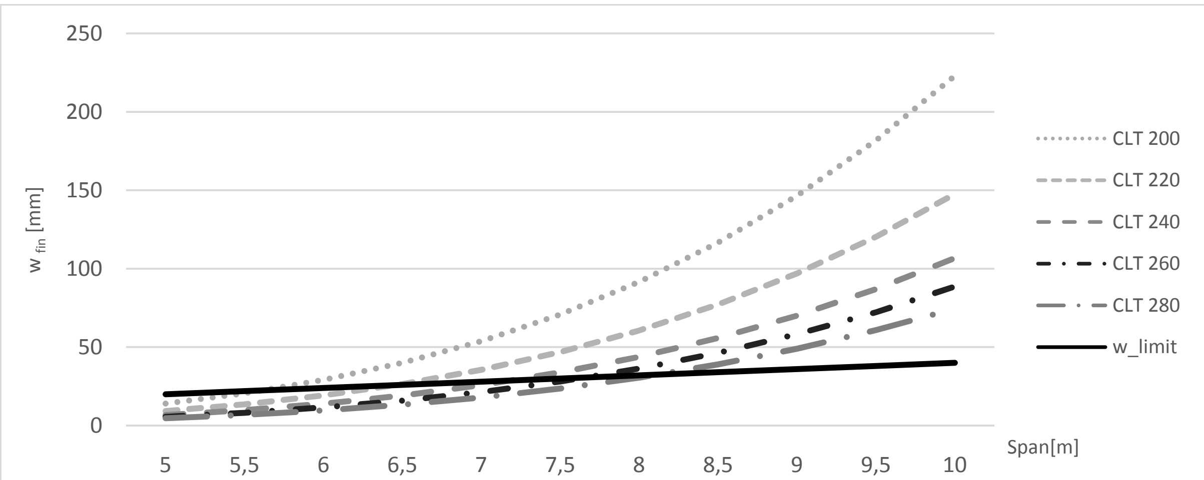

Fig. 10: Comparison of final deflection depending on thickness of noncoupled CLT-concrete and length of span.

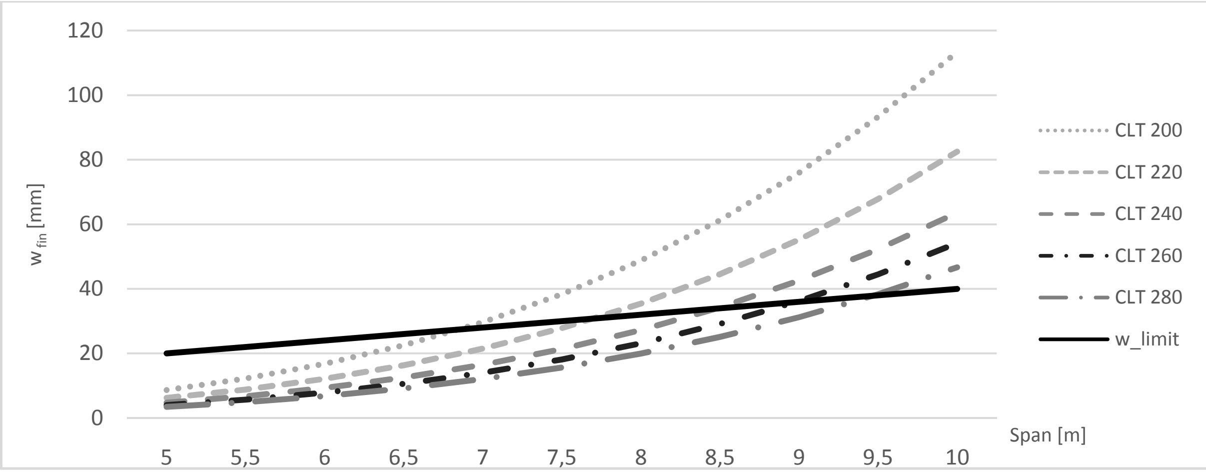

Fig. 11: Comparison of final deflection depending on thickness of coupled CLT-concrete and length of span.

It is necessary to consider assessments at the ultimate limit state as well as usability. As it is obviously presented in Figs. 13 and 14, there may be case where the conditions are fulfilled only for SLS (EN 1991-1-1, 2002). In Fig. 12 are presented distribution of bending stresses cross the height of cross-section.

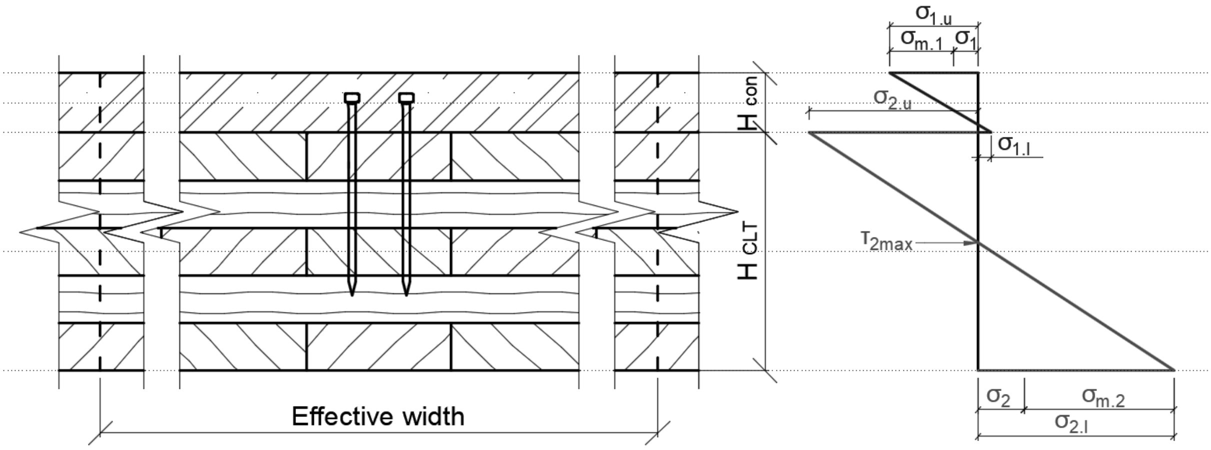

Fig. 12: Cross-section of CLT and distribution of bending stresses.

Similar cross-section of 240 mm thickness was taken for all variants in the comparison. Load width is 1m and span is 5 m, these parameters are similar for this comparison. Segments are shown in their end of live state.

Timber beam variants have higher value stresses along the cross-section comparing to CLT slab variants. Stress at the upper edge of the concrete section can be observed multiply values in the evaluation by 22.1% is the difference between coupled and non-coupled timber-concrete beam, in favour of coupling variant. Selected samples of beam variants show exceeding stress limits. It can be observed that in the case of the coupled beam variant was a decrease of almost 100% compared to the noncoupled variant of value 214.6%. Exceeded values can be seen in evaluation of final deflection. Noncoupled timber beam variant reach values of 230%. Decrease of this value to 63.2% is by using shear connectors in coupled timber-concrete beam variant. Requirement for limit state of final decline is fulfilled. It is clear, that coupling elements are significantly improving segment according to Tab. 1.

Tab. 1: Evaluation of Assessment at timber-concrete variants with 5 m span.

Coupled timber-concrete ceiling						Non-coupled timber-concrete ceiling					
Cross-section		ULS - end of service life			SLS - end of service life	Cross-section		ULS- end of service life			SLS - end of service life
H_T	W_T	$\sigma_{1.u}/f_{cd}$	$\sigma_{2M}/f_{md+}\sigma_{2.l}/f_{t.0.d}$	τ_{2max}/f_{vd}	w_{fin}/w_{lim}	H_T	W_T	$\sigma_{1.u}/f_{cd}$	$\sigma_{2M}/f_{md+}\sigma_{2.l}/f_{t.0.d}$	τ_{2max}/f_{vd}	w_{fin}/w_{lim}
200	120	0.396	1.578	0.500	0.916	200	120	0.843	2.887	0.694	3.705
220	120	0.344	1.368	0.466	0.756	220	120	0.659	2.481	0.656	2.898
240	120	0.302	1.199	0.437	0.632	240	120	0.523	2.146	0.618	2.300
260	120	0.268	1.059	0.411	0.535	260	120	0.420	1.868	0.583	1.850
280	120	0.240	0.943	0.389	0.456	280	120	0.342	1.637	0.550	1.507

Values of stresses at the upper edge of concrete part of section of different CLT variants are slightly similar to each other (Tab. 2). On the other hand, these differences are not so obvious as in timber beam variants. Coupled CLT-concrete slab has 7.12% capacity instead of 13% by noncoupled CLT-concrete slab. Strain at lower part of timber segment is decisive factor. Requirements for ULS and SLS in case of CLT variants are satisfied. Decrease in values is not so observable as in case of beam variants. Coupled variant has decrease of values 5.7%. It is due to higher efficiency of slabs involved their higher stiffness.

Tab. 2: Evaluation of assessment at CLT-concrete variants with 5 m span.

Coupled CLT-concrete ceiling					Non-coupled CLT-concrete ceiling				
Cross-section	ULS - end of service life			SLS - end of service life	Cross-section	ULS - end of service life			SLS - end of service life
H_{CLT}	$\sigma_{1.u}/f_{cd}$	$\sigma_{2M}/f_{md}+\sigma_{2.l}/f_{t.0.d}$	τ_{2max}/f_{vd}	w_{fin}/w_{lim}	H_{CLT}	$\sigma_{1.u}/f_{cd}$	$\sigma_{2M}/f_{md}+\sigma_{2.l}/f_{t.0.d}$	τ_{2max}/f_{vd}	w_{fin}/w_{lim}
200	0.213	0.478	0.122	0.432	200	0.153	0.600	0.144	0.702
220	0.162	0.356	0.098	0.310	220	0.101	0.435	0.115	0.464
240	0.130	0.284	0.085	0.236	240	0.072	0.341	0.098	0.335
260	0.114	0.259	0.084	0.200	260	0.060	0.306	0.095	0.278
280	0.101	0.237	0.083	0.171	280	0.050	0.276	0.093	0.234

Tab. 3: Evaluation of assessment at CLT-concrete variants with 8 m span.

Coupled CLT-concrete ceiling					Non-coupled CLT-concrete ceiling				
Cross-section	ULS - end of service life			SLS - end of service life	Cross-section	ULS - end of service life			SLS - end of service life
H_{CLT}	$\sigma_{1.u}/f_{cd}$	$\sigma_{2M}/f_{md}+\sigma_{2.l}/f_{t.0.d}$	τ_{2max}/f_{vd}	w_{fin}/w_{lim}	H_{CLT}	$\sigma_{1.u}/f_{cd}$	$\sigma_{2M}/f_{md}+\sigma_{2.l}/f_{t.0.d}$	τ_{2max}/f_{vd}	w_{fin}/w_{lim}
200	0.623	1.196	0.198	1.524	200	0.393	1.531	0.230	2.864
220	0.494	0.885	0.157	1.107	220	0.259	1.110	0.183	1.895
240	0.408	0.703	0.134	0.851	240	0.186	0.872	0.157	1.370
260	0.362	0.644	0.133	0.724	260	0.154	0.782	0.153	1.137
280	0.325	0.593	0.132	0.622	280	0.129	0.707	0.148	0.957

In this comparison were used samples of variants as beam and slab ceilings showed in (Tabs. 1 and 2) with the same span of 5 m. CLT variants are not suitable for shorter spans as it was presented and have potential for considerably higher span and loads. Longer span would be more appropriate for variants consisting of CLT panels. For example (Tab. 3), exceeded capacity can be seen in coupled and noncoupled CLT concrete slab with 8 m span. Overall fulfilled conditions for SLS and ULS are completed in coupled CLT concrete variant. By comparison values of capacity with case of noncoupled variant values are higher by 137% and are no more suitable for SLS. These values are 51.9% higher than in coupled variant. In case of ULS the decisive stresses capacity is in the lower part of CLT panel. Capacity is suitable, but it has higher percentage usage than other assessments.

It is not only resistance or load-bearing capacity that should be taken in consideration during decision-making about the type of ceiling structure (Tab. 4). The design may be suitable for these factors, but it is necessary to consider others, e.g., requirement of structure thickness of each storey, because the thickness of ceiling can also strongly influence total building costs. Advantage of using slab CLT system is not only low thickness and good rigidity, but also simplicity of placement technical equipment of buildings, because of the absence of protruding beams (Bajzecerová and Kanócz 2017).

Tab. 4: Comparison of variants based on suitability for use (darker color indicates higher suitability for use).

Alternatives Parameters	Non-coupled timber beam concrete ceiling	Coupled timber beam concrete ceiling	Non-coupled CLT-concrete ceiling	Coupled CLT-concrete ceiling
Length of span				
Thickness of ceiling				
Time of realisation				
Fire resistance				
Price				

Level of difficulty in making the ceiling structure is another indicator. It is necessary to use formwork while using the beam system. When classic formwork is used, it must be also removed afterwards. This aspect remains even in the coupled variant where the application of a considerable number of shear connectors are added to the entire assembly process. Necessity to install formwork is eliminated while applying the slab system. In terms of implementation, it is the simplest and least laborious variant. This system can be made more efficient by using shear connectors, but at the expense of laboriousness in laying the self-tapping screws.

In fire situation, compared to steel or concrete is timber as material more effective. Timber not prone to lose strength after reaching a certain temperature, and neither is explosive strub off the surface as it is the habit for the concrete. Charred layer which slows down the overheating of the element at outer side of timber protects surface (Makovická Osvaldová et al. 2016, Chen et al. 2021). It is important to note, that section does not lose its resistance abruptly but continuously (Makovicka Osvaldová 2020).

During the research of a suitable variant, it is also necessary to consider the financial complexity. It is obvious that the cheapest will be the application of the simplest solution - the beam ceiling noncoupled, but it is inefficient way. The usage of CLT panels can make construction considerably more expensive, but nevertheless it is possible to realize ceiling structures with larger spans. It is also required to consider the necessity of using the shear connectors. Price of self-tapping screws is not negligible due to their quantity and quantity of additional work. Also, must be account necessity of usage temporary supports while applying coupled variants.

CONCLUSIONS

Coupling appears to be an effective way to achieve higher strength of the ceiling structure. While comparing the beam variants, it was found that the proposed coupling was able to eliminate the stresses to approximately half the values compared to the uncoupled variant. The slab variants have been found to be unnecessarily oversized at 5 m spans. Further research will need to focus on the use of slimmer boards (Van Thai et al. 2020). It would be beneficial to focus on the effectiveness of the coupling, in which case, a higher degree of coupling could also be verified. Alternatively, verify other methods of coupling (Kanócz et al. 2013). Coupling with the aid of screws appears to be a highly laborious alternative and it would be appropriate to compare the coupling efficiency also with the variant where the shear connectors would be used as a perforated steel strip shear connectors or grooves.

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