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Strengthening of timber floors with CLT panels – a numerical study

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Abstract

The purpose of this article is to provide an insight into the field of timber floor strengthening with cross-laminated timber (CLT) panels. A classic timber floor strengthened with CLT panels is therefore analysed according to the current building standards in the European Union, the Eurocodes. Seven different CLT panels, with thicknesses from 60 mm to 120 mm, are taken into consideration for the numerical study. Self-tapping screws with a diameter of 6 mm and length of 200 mm are used as shear connectors. The gamma method is used for calculating the effective bending stiffness. The design procedure is briefly presented, and the results for different configurations are compared.

Keywords: timber floors, cross laminated timber, self-tapping screws, composite floor

Ojačavanje podnih konstrukcija CLT pločama - numerička studija

Sažetak

Cilj je ovog rada pokazati kako ojačati podne konstrukcije koristeći unakrsno laminirane drvene panele (CLT paneli). Kao predmet studije uzete su klasične drvene podne konstrukcije ojačane sa CLT panelima i uspoređene s Eurocode standardima, službenim graditeljskim standardom u EU-u. Sedam različitih tipova panela debljine od 60 do 120 mm su analizirani u numeričkoj studiji. Kao sredstvo sprezanja uzeti su samourezujući vijci promjera 6 mm i duljine 200 mm. Za proračun efektivne savojne krutosti korištena je gama metoda. U radu je kratko prikazana procedura dimenzioniranja te su uspoređeni rezultati različitih konfiguracija podnih konstrukcija.

Ključne riječi: drveni podovi, unakrsno laminirano drvo, samourezujući vijci, spregnute podne ploče

1. Introduction

Timber floors present a significant part of the of the existing building fund, and they must often be structurally improved, due to various reasons. For example, due to a possible change of the category in use and consequently higher imposed loads. The timber-concrete composite (TCC) section has gained importance as a strengthening technique in the past years [1], as it strengthens the “out of plane” and “in-plane” behaviour of the timber floor simultaneously. On the other hand, the disadvantage with TCC is that a high amount of moisture is brought in to the building (due to concrete pouring) and that it is an irreversible strengthening method. In some instances, attention must also be given to the cultural heritage criteria. For example, in Italy, the timber-concrete approach for strengthening old timber floors is often rejected by responsible authorities due to claims that the measure is not reversible [2]. Instead of the concrete part of the TCC section, additional timber elements in the form of laminated or cross-laminated timber (CLT) are often used, which presents a dry technique for forming composite cross sections and is, therefore, preferred for timber floors of historical or cultural interest ([2,3]). The aim of this paper is, therefore, the provision of an insight into the field of timber floor strengthening with CLT panels. A numerical example of timber joists (of a timber floor) strengthened with CLT panels is studied. The CLT panels are installed on top of the existing timber joists and connected to the timber joists with self-tapping screws.

2. Numerical example setup

2.1. Timber floor

The numerical example deals with a 4.5 m long timber floor with a joist spacing of 90 cm. The joists have a cross section of 16 cm x 20 cm. Examples of typical timber floors are given in[4], where also old timber floor joist dimensions in relation to the floor span are presented.
The strength class of the timber joists was defined as C24 and the serviceability class as S2.

2.2. CLT panels

For the strengthening measure, seven different CLT panels with a width of 90 cm are studied, which is the same as the timber joist spacing. Their geometric properties are presented in Table 1. An index is assigned to each CLT panel. Note that the index 1 is assigned to the case with no CLT panel present (solely the timber joists). The letters L and C designate the longitudinal and transverse (cross) layers thickness. The outermost layers are always longitudinally oriented (in the direction of the floor span).

Table 1. Studied CLT panels

CLT panel index	Thickness [mm]	Layers	L [mm]	C [mm]	L [mm]	C [mm]	L [mm]
1	/	/	/	/	/	/	/
2	60	3	20	20	20	/	/
3	80	3	20	40	20	/	/
4	90	3	30	30	30	/	/
5	100	3	30	40	30	/	/
6	120	3	40	40	40	/	/
7	100	5	20	20	20	20	20
8	120	5	30	20	20	20	30

The mechanical properties of the timber class C24 are adopted for the mechanical properties of the CLT panels. Specific CLT properties can be found in Table 2.

Table 2. Material properties of CLT lamels

Characteristic rolling shear strength	$f_{vR.k}$	1.10	$[MPa]$
Rolling shear modulus	$G_{r.mean}$	50.00	$[MPa]$

2.3. Self-tapping screws

Self-tapping screws are used for the connections between the timber joists and CLT panels. The geometric properties are given in Table 3. Mechanical properties as the characteristic yield moment, characteristic embedding strength, characteristic axial withdrawal capacity, axial slip modulus are provided by the manufacturer in [5]. The screws are inclined at an angle of 45° with respect to the shear plane and oriented in a way that they are subjected to shear-tension loads. The screw row spacing is 8 cm (3 screws are placed in every row).

Table 3. Dimensions of self-tapping screws

Thread diameter [mm]	Core diameter [mm]	Length [mm]	Thread length [mm]
6	3.8	200	185

3. Structural calculation

To assess the load-bearing capacity of the given timber floor, an analysis is performed according to Eurocode 5 [6]. The calculations are performed in compliance with the so-called "gamma method" from Annex B of Eurocode 5 [6]. The shear connectors (self-tapping screws) stiffness calculations and structural checks are done according to the models provided in [7,8]. The combination factors for area category C3 were used.

The calculations of maximum imposed loads (Q) are carried out for different configurations with CLT panels (indexes from Table 1) and the Ultimate limit state and the Serviceability limit state. The static system is a simply supported beam. The design strengths are used for strength verifications ($X_d = k_{mod} \cdot \frac{X_k}{\gamma_M}$).

3.1. CLT panel effective bending stiffness

To calculate the effective bending stiffness $(EI)_{ef}$ of the Timber-CLT composite floor, the gamma method is applied on two levels. The first level is solely the CLT panel cross-section which is basically already a composite cross-section with flexible connectors (the transverse layers of the CLT panels). According to [9] the γ coefficients for consideration of the flexibility of the transverse CLT layers are calculated with:

$$\gamma_i = \frac{1}{1 + \frac{(\pi^2 \cdot E_i \cdot A_i \cdot d_{i,2})}{l^2 \cdot b_{clt} \cdot G_{R,i,2}}} \tag{1}$$

where E_i is the elastic modulus of the i-th CLT layer, A_i the cross section area of the i-th CLT layer, $d_{i,2}$ the thickness of the transverse CLT layer between the i-th and second longitudinal CLT layer and $G_{R,i,2}$ the rolling shear modulus of the transverse CLT layer between the i-th and second (longitudinal) CLT layer. This method is applicable for CLT panels with 3 or 5 layers, with the difference that the results for 3 layers give unsymmetrical interim results. In both cases, the second longitudinal layer (counted from the upper edge of the CLT panel) is the primary layer ($\gamma_2 = 1$) and other layers are flexibly connected to it for the purpose of calculation.

The effective bending stiffness $(EI)_{clt,ef}$ of the CLT floor is then defined with:

$$(EI)_{clt,ef} = \sum_{I=1}^{N} (E_i \cdot I_i + \gamma_i \cdot E_i \cdot A_i \cdot a_i^2) \tag{2}$$

where E_i is the modulus of elasticity of the i-th longitudinal CLT layer, A_i cross-section area of the i-th longitudinal CLT layer, a_i the distance between the centres of gravity of the i-th longitudinal CLT layer and composite CLT cross-section, I_i moment of inertia of the i-th longitudinal CLT layer.

3.2. Composite floor effective bending stiffness

To calculate the effective bending stiffness $(EI)_{ef}$ of the composite floor (timber joists strengthened with CLT panels), the gamma method is applied once again. The slip modulus K_i of the self-tapping screws is calculated according to [8] as a combination of the slip modulus for lateral loading and withdrawal loading of the self-tapping screws. The effective bending stiffness is calculated with Eq. (2), where the CLT layers are substituted with cross-section areas of the CLT longitudinal layers and the timber joist.

4. Results

Maximum imposed loads (Q) are calculated for the Ultimate limit state – Normal stress criterion of the timber joist (bottom edge normal stress which is a combination of tensile and bending stress) and the Serviceability limit state – Final deflection criterion. For the maximum imposed load from the Ultimate limit state – Normal stress criterion of the timber joist several other structural checks are made:

- timber joist shear stress (conservatively the whole shear force is said to be resisted by the timber joist) – the "TS Util." criterion denotes the utilisation of the timber joist shear strength
- CLT upper edge normal (bending and compression) stress – "CLT Util." denotes the utilisation of the CLT panel compression and bending strength
- CLT rolling shear (the shear stress is calculated on the bottom edge of the CLT panel which is conservative as the rolling shear occurs in the transverse (flexible) layers)
- screw strength – the RS Util." criterion denotes the utilisation of the CLT rolling shear strength and "JFM." denotes the Johansen failure mode of the screw

The results for the ULS and SLS are given in Table 4. The index numbers are related to Table 1 and denote which CLT panel is considered for the calculation (index 1 denotes the case where only the timber joist is checked).

Table 4. Maximum imposed loads for the ULS (with additional checks) and SLS criteria

	ULS						SLS
CLT panel index	Q $\left[\frac{kN}{m^2}\right]$	CLT Util.	Screw Util.	JFM	TS Util.	RS Util.	Q $\left[\frac{kN}{m^2}\right]$
1	3.576	/	/	/	0.427	/	1.572
2	6.157	0.404	0.938	F	0.687	0.159	6.889
3	6.951	0.465	0.723	F	0.767	0.167	8.194
4	7.657	0.409	0.856	F	0.836	0.177	9.754
5	8.185	0.434	1.01	F	0.888	0.178	10.399
6	9.701	0.437	1.349	E	1.036	0.185	11.735
7	7.623	0.441	1.792	F	0.836	0.151	10.143
8	9.514	0.437	1.349	E	1.018	0.185	11.503

5. Conclusion

The results from Table 4 show that the timber floor can be effectively strengthened with the help of CLT panels, as already the thinnest CLT panel (CLT index 2, Table 1) strengthens the timber floor to achieve a load bearing capacity suitable for the area category C3 (minimum imposed load of 5 $\frac{kN}{m^2}$. It can also be seen that the second most critical criterion (after the tensile and bending strength of the timber joists) is the strength of the self-tapping screws. They govern the design when CLT panels with indexes 6-8 are used. For the strengthening measure with CLT panels with indexes 2-5 and 7, the failure mode of the screws is the failure mode F (embedment failure in both members and two plastic hinges in the shear plane). For CLT panels with indexes 6 and 8 the failure mode of the screws is the

failure mode E (embedment failure in the timber joist and one plastic hinge in member 1 – CLT panel), which is a consequence of the too low penetration length of the 200 mm long screw in the timber joist (for the 120 mm thick CLT panel: $200\,mm - \frac{120\,mm}{\cos 45°} \cong 30\,mm$). Criteria such as the "CLT Util.", "RS Util." and "TS Util." seem to be of minor importance. The SLS results from Table 4 show that the CLT panel positively affects deflections of the timber floor. It is interesting that the SLS maximum imposed load is lower than the ULS load for the timber floor without CLT panels (CLT index 1) and on the other hand the SLS maximum imposed loads for the strengthened timber floor are higher than the ULS maximum imposed loads (CLT indexes 2-8).
It has been shown that despite the strength of the individual parts of the composite cross-section (timber joists and CLT panels) also the self-tapping screws present an important load bearing element whose strength utilisation must be controlled. Considering the results from the structural calculation for the Timber-CLT composite floor it seems that this floor system has the potential to fulfil at least the structural criterion.

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