Conference Proceedings 4th ICTB (2022)
https://doi.org/10.24451/w9sn-2964

ICTB 2021 PLUS
4th International Conference on Timber Bridges
Biel/Bienne, Switzerland, 9 -12 May 2022

Structural yield of a pedestrian bridge made of CLT-concrete, connected by screws and by notches

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Abstract

The structural design of a simply supported pedestrian bridge made of Cross-Laminated-Timber-Concrete-Composites (CLTCC) was studied for two different connections between CLT and concrete: i) 45º crossed-pairs of screws of 9 mm of diameter; and ii) longitudinal notches in the CLT (40 mm depth and 100 mm width). The composites were manufactured from CLT of Radiata pine from Spain, visually graded as C24, and concrete H25/B/25/I. Experimental push-out tests were made on 30 specimens of CLT-concrete according to EN 26891, 15 for each type of connection, to obtain the maximum load and the force-displacement curve, which were used to estimate the shear strength (f_v) and the slip modulus (K_{ser}) of the connection. In both cases, shear strength and slip modulus, the notched connections (1) resulted in higher values than those of the screws connections. The values of shear strength were 11.6 kN (CoV=36%) and 29.8 kN (CoV=34%) for the screws and notched connections, respectively. The values of slip modulus were 20,3 kN/mm (CoV=18%) and 68.4 kN/mm (CoV=21%) for screws and notches, respectively. Experimental screws connection showed a value of slip modulus higher than that obtained from the theoretical equation given by the Eurocode-5 (K_{ser} = 13.5 kN/mm). The experimental values were used to estimate the stress, strength and stiffness of the CLT-concrete slabs used as pedestrian bridges and residential buildings for both connection solutions. The notched connections showed a better performance than screwed connections in the bridge structural design, with a span over thickness ratio 4-5% higher for the same number of CLT layers.

1 Introduction

In the last decades, timber construction is experiencing a global worth, due in part to the need of reducing carbon emissions in a political model of transition into bioeconomy [1]. The growing use of cross laminated timber (CLT) in construction has been reported by several authors [2][3][4][5], mainly used as slabs and walls in buildings. The need to obtain a better structural behaviour, mainly associated to serviceability, of CLT panels used as floors in buildings on one hand, and the need to improve the sustainability criteria in the current concrete building sector on the other hand, had led to an increase in the use of CLT-concrete composites (CLTCC) in construction.

The first patent for Timber-Concrete-Composites (TCC) can be found in 1922; however, during the XX century reinforced concrete and steel structures were dominant in construction. TCCs have experienced a great growth in the last 20 years [6], initially focused on rehabilitation of buildings, in a system where timber beams (solid timber or glued laminated timber beams) are connected to a compression layer of concrete.

Nowadays, the current version of the Eurocode 5, EN 1995-1-1 [7], does not include the regulations for the design of CLT panels or TCC, which will be included in the new version [8], currently in discussion in the WG1 and WG2 of CEN/TC 250/SC 5; however, it does not include the case of CLT and Concrete Composites (CLTCC). Several authors have reported results of studies of TCC combining concrete slabs with timber beams [9] [10], but finding examples for CLTCC is not as common [11].

This work proposes to study the influence of two different connection types (notched and screwed connections) in the design of a pedestrian bridge designed as a CLT-concrete composite slab, from the experimental values of the slip modulus and the shear strength of the CLT-concrete connections.

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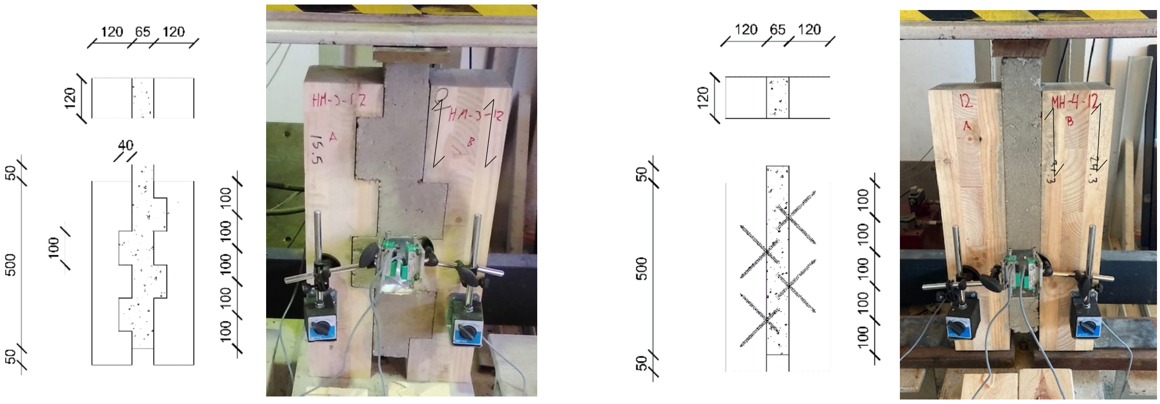
2 Material and method

2.1 CLT-Concrete Composite types

Thirty specimens of CLT-Concrete composites of Radiata pine (*Pinus radiata* D. Don) were manufactured in the facilities of the Cesefor Foundation (Spain), using timber of strength class C24 for the longitudinal layers and C16 for the transversal layers, and mass concrete H25/B/25/I. Two configurations for the connection between CLT and concrete were considered, a) notched and b) screwed (Fig. 1), fifteen from type a) and fifteen from type b). The notched connection had a depth of 40 mm (equal to the thickness of the first lamella), and the thickness of the specimens was 120 mm, the separation between notches was 200 mm. No fastener was used, assuming that the results provide conservative properties. For the screwed connection, crossed pairs at 45º timber-concrete screws CTC9160 from Rothoblaas were used, separated 200 mm along the longitudinal direction.

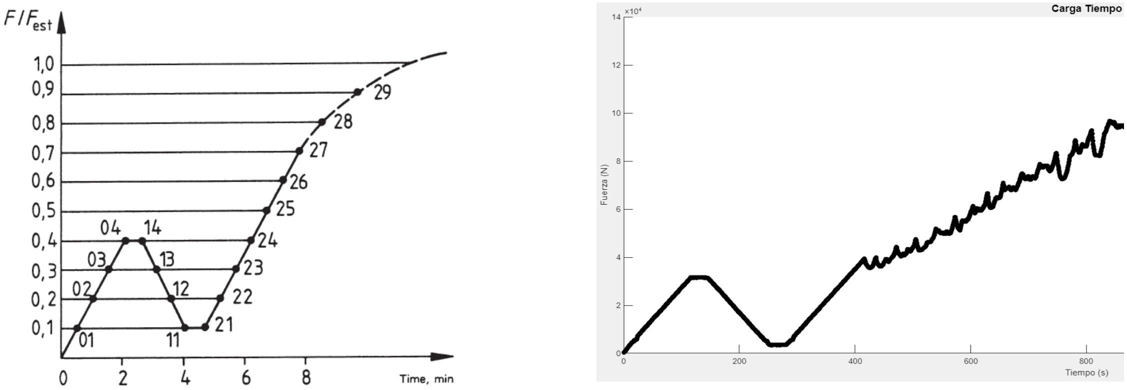


a) Notched connection b) Screwed connection

Figure 1: Experimental shear test specimens

2.2 Experimental testing

Fifteen double shear tests were carried out according to UNE EN 26891:1991 [12] for each connection type. The load was applied as shown in Fig. 2. The mean value of the relative displacement between CLT and Concrete measured with 4 extensometers located by pairs in both front and back faces as shown in Fig. 1 was used to calculate individual values of slip modulus (K_{ser}) in the initial elastic period (Between points 01 and 04 of Fig 2.a). Average value of K_{ser} was calculated.



a) Loading procedure according to EN 26891 b) Experimental loading procedure

Figure 2: Loading procedure

It was considered that each connection takes up a fourth part of the load applied. Individual strength values (F_i) were calculated according to Eq. 1 and the characteristic values were derived according to EN 14358:2016 [13] assuming a log-normal distribution of strength values.

$$F_i = \frac{F_{max}}{4} \qquad \text{Eq. 1}$$

2.3 Structural design methodology for a pedestrian bridge

2.3.1 Geometry

A simply supported 2 m wide CLTCC pedestrian bridge with both connection types over a span l was designed (Fig 3.). The total height of CLT is nh_l, being n the number of layers and h_l the CLT layer thickness (40 mm). Each layer was placed orthogonally to the next, being the upper and lower layers disposed in the longitudinal direction. The separation of the connectors was considered constant (200 mm) and the depth was considered equal to the layer thickness, in order to maintain the same conditions of the experimental shear tests. The thickness of the concrete compression layer (h_c) was defined with the aim that the neutral axis of the total CLTCC section is in the interface of the first and second layer of the CLT panel.

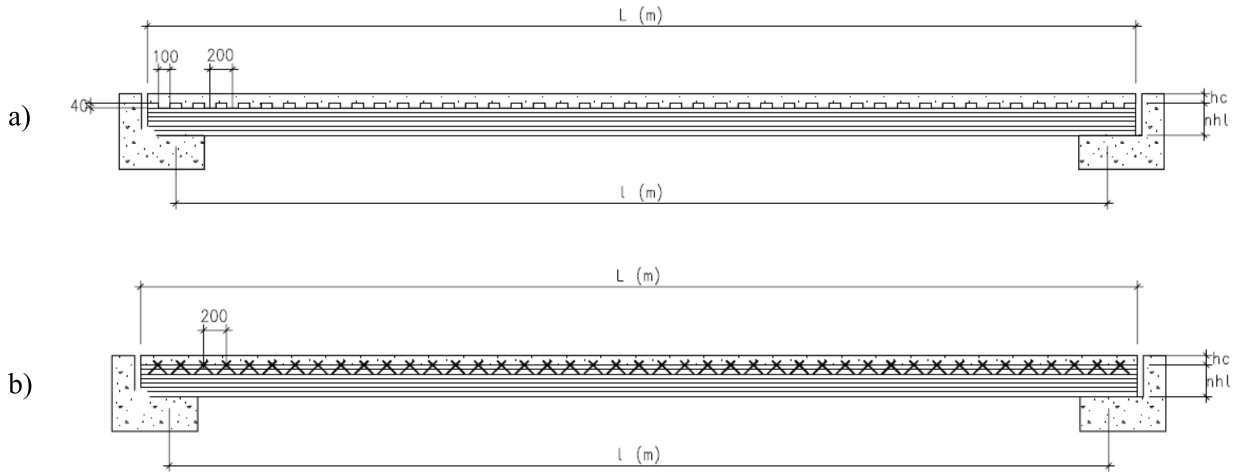


Figure 3: Pedestrian bridge geometry: a) notched connections and b) screwed connections

2.3.2 Design hypothesis

The timber physical and mechanical properties of strength classes C24 and C16 were taken from EN 338:2016 [14] and the rolling shear properties from the pro:Holz Cross-Laminated Timber Structural Design Manual [15]. Mechanical properties of concrete were calculated as given by EN 1992:2004(16) for concrete of $f_{ck} = 25\ N/mm^2$.

The basis for the structural design was taken from Eurocode 0 (17) for ultimate limit state (ULS) and deformation in serviceability limit state (SLS), considering a uniform imposed load of 5 kN/m^2 taken from Eurocode 1 [18]. The vibration serviceability limit state was not considered. The stiffness of the composite section was calculated using the Gamma method defined in the Annex B of Eurocode 5 for both ULS and SLS. Apart from these, several hypotheses were made:

i) Transverse layer contribution was neglected in the stiffness.
ii) Shear deformation was considered for the transverse layers of CLT and not in the longitudinal layers.
iii) Values of slip modulus were obtained from the experimental campaign. Since the tests were made in specimens of 120 mm wide, the results were multiplied by 8.33 to obtain the K_{ser} applied to an unitarian bridge width (1 m)($K_{ser,bridge} = K_{ser,exp} 1000/120$)
iv) For notched connection the slip modulus in ULS was considered equal to that of SLS, $K_{ser,ULS} = K_{ser,SLS}$
v) For screwed connection the slip modulus in ULS was considered as two thirds of that of SLS $K_{ser,ULS} = 2/3\ K_{ser,SLS}$
vi) Concrete creep deformation was not considered in the calculation.
vii) Service class 2 was considered.
viii) Imposed loads were considered as short term.
ix) For the design of the CLTCC, the most restrictive value of rolling shear of the CLT panel was taken into account to calculate the stiffness (upper layer of CLT)

x) Hardening in the concrete is not considered

To calculate the effective stiffness (EI_{ef}) of the composite section, the Gamma method was used. A slip between 1) CLT and concrete; and 2) the longitudinal layers of the CLT (result of the rolling shear deformation of the transverse layer) were considered. The slip modulus between longitudinal layers of CLT was calculated using Eq. 2.

$$K_{ser,CLT} = \frac{G_{R,mean}B}{h_l} \qquad \text{Eq. 2}$$

Being $G_{R,mean}$ the rolling shear modulus, B the width of the panel and h_l the layer's thickness.

$$EI_{ef} = E_c I_c + \gamma_c E_c A_c a_c^2 + \sum_{i=1}^{N} (E_i I_i + \gamma_i E_i A_i a_i^2) \qquad \text{Eq. 3}$$

$$\gamma_C = \left(1 + \frac{\pi^2 E_c A_c s}{K_{ser} l^2}\right)^{-1} \qquad \text{Eq. 4}$$

$$\gamma_i = \left(1 + \frac{\pi^2 E_i A_i}{K_{ser,CLT} l^2}\right)^{-1} \qquad \text{Eq. 5}$$

where, E_C is the elastic modulus of concrete, A_c is the area of the cross section of concrete, s is the separation between connections, K_{ser} is the slip modulus of the connection (in either SLS or ULS), l is the span, I_C the individual moment of inertia of concrete, a_c the distance between the barycentre of the whole CLTCC section and the barycentre of the concrete layer section, N is the amount of longitudinal layers of CLT, E_i is the elastic modulus of the longitudinal layers, I_i is the individual moment of inertia of each layer, A_i is the area of the cross section of each CLT layer, a_i is the distance between the barycentre of the whole CLTCC section and the barycentre of the CLT longitudinal layer section.

2.3.3 Limit States

Two ultimate limit states were considered 1) $1.35PL$ 2) $1.35PL + 1.5IL$, being PL the permanent loads and IL the imposed loads. The following verifications were made: shear in the connection ($\max(V_{con}/F_{V,d}) \leq 1$); rolling shear in the CLT transverse layer ($\max(f_{v,rs}/f_{v,rs,d}) \leq 1$); Concrete compression ($\max(f_c/f_{c,d})$); and CLT tension in the bottom layer ($\max(f_m/f_{m,d}) \leq 1$). Given the geometry of the section, the compression in the CLT top layer always verified with the values of compression parallel to grain.

Two different load states were considered for the instantaneous and creep effect of the permanent and imposed loads. The creep effects for the imposed loads were null. Three verifications were made: integrity of the constructive elements (Eq. 6), user comfort (Eq. 7) and construction appearance (Eq. 8).

$$(\delta_{i,IL} + \delta_{d,PL}) / \frac{l}{400} \leq 1 \qquad \text{Eq. 6}$$

$$(\delta_{i,IL}) / \frac{l}{350} \leq 1 \qquad \text{Eq. 7}$$

$$(\delta_{i,IL} + \delta_{i,PL} + \delta_{d,PL}) / \frac{l}{300} \leq 1 \qquad \text{Eq. 8}$$

Where, $\delta_{i,IL}$ is the instantaneous effect of the imposed loads, $\delta_{i,PL}$ is the instantaneous effect of the permanent load, $\delta_{d,PL}$ is the creep effect of the permanent load (considering $K_{def} = 1$) and l is the span.

3 Results

3.1 Experimental results of the connections

Experimental results of the shear strength ($F_{V,k}$) and the slip modulus ($K_{ser,i}$) of the CLT-concrete connections, described in point 2.1 and 2.2, are presented in Table 1. The eccentricity produced by the asymmetry in the connections of the test specimens was neglected, assuming that the results should be on the safety side for the structural design.

Table 1: Experimental results

Property	Notched connections	Screwed connections
$F_{V,mean}$ (kN)	29.8	11.6
CoV (%)	34	36
$F_{V,k}$ (kN)	9.3	4.9
$K_{ser,i}$ (kN/mm)	68.4	20.3
CoV (%)	21	18

It was observed that the notched connections showed higher values of strength (90% higher) and slip modulus (237% higher) than the screwed connections. Given that the draft for the new Eurocode 5 (8) provides an equation to estimate the slip modulus of a concrete to timber connection, experimental result for screwed connections was compared with the theoretical value (Eq. 9). The experimental slip modulus was 50% higher than that proposed by the design code.

$$K_{ser,E5} = \frac{2\rho_m^{1.5}d}{23} = 13.5\,\frac{kN}{mm} \qquad \text{Eq. 9}$$

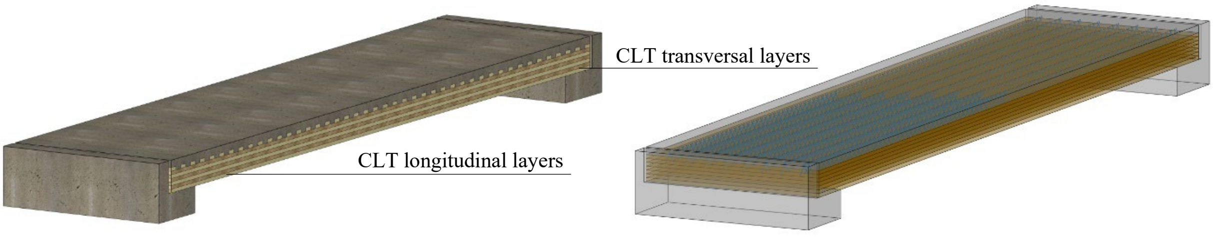
3.2 Design results

3.2.1 Geometry

The simply supported pedestrian bridge with both connection types was designed for different CLTCC thickness (Fig. 4). The geometry of the CLTCC depending on the number of layers of the CLT panels is shown in Table 2, where increasing the number of CLT layers implies an increase in the concrete layer thickness. The lightest colour of the CLT in Fig. 4a indicates the longitudinal layers and the darkness colour the transversal layers. The screwed bridge of the Fig. 4b is made with transparent materials with the aim to see the location of the screws and the disposition of the layers is equal to that in Fig. 4a.

Table 2: Cross-section geometry of the bridge

	CLT layers		
	5	7	9
Thickness CLT (mm)	200	280	360
Thickness concrete, h_c (mm)	46	81	116
Thickness CLTCC (mm)	246	361	476



a) Notched connection b) Screwed connection

Figure 4: CLTCC pedestrian bridge: a) notched connections and b) screwed connections

3.2.2 Structural design

The structural design of the CLTCC bridge was studied varying the span in steps of 100 mm for 5-, 7- and 9- layers of CLT and for the two connection types, to obtain the maximum span complying with the requirements described in point 2.3.3. The verifications are shown in Table 3.

Table 3: Structural verifications for the CLTCC bridge

	Notched connections			Screwed connections		
CLT layers	5	7	9	5	7	9
$EI_{ef,SLS}$ (kNm^2)	9593	25880	53768	8100	21669	45121
$EI_{ef,ULS}$ (kNm^2)	9593	25880	53768	7599	20248	42098
max $(V_{con}/F_{V,d})$	0.81	0.99	0.99	0.78	0.96	0.99
max $(f_{v,rs}/f_{v,rs,d})$	0.03	0.03	0.03	0.03	0.04	0.04
max $(f_c/f_{c,d})$	0.75	0.77	0.68	0.86	0.88	0.80
max $(f_m/f_{m,d})$	0.61	0.67	0.61	0.70	0.77	0.72
Eq. 6	0.97	0.98	0.78	1.00	0.98	0.83
Eq. 7	0.62	0.58	0.45	0.64	0.58	0.48
Eq. 8	0.92	0.97	0.79	0.95	0.97	0.83
Maximum span (m)	6.4	8.7	10.2	6.1	8.2	9.8
Span/thickness (STR)	26.0	24.1	21.4	24.8	22.7	20.6

As expected, notched connections showed a better structural yield than screwed connections. The span over thickness ratio (STR) was defined to compare the obtained results. For the same number of CLT layers, the STR of notched connections showed values between 4-5% better than those of screwed connections.

In both type of connections, the limits are imposed by the SLS for 5 layers CLT, shifting to ULS for 9 layers CLT, showing an equilibrium in the limits for 7 layers CLT. The increase from 5- to 9- layers produced a similar span increase in both cases (3.8 m and 3.7 m respectively). However, the 5 layers CLT showed the better structural yield measured as STR. The STR values are 21.5% and 20.4% higher for 5 layers CLT than that of 9 layers CLT for notched and screwed connections, respectively.

The structural yield of these CLTCC used as slabs in residential buildings (imposed load 2 kN/m^2) increased between 14% and 21% with respect to the use in pedestrian bridges (Table 4). It should be noticed that the use of CLTCC slabs for residential buildings is always limited by SLS.

Table 4: Structural verifications for the CLTCC bridge

	Notched connections			Screwed connections		
CLT layers	5	7	9	5	7	9
Maximum residential slab span (m)	7.4	9.7	12.3	7.0	9.3	11.7
$STR_{residential}$	30.1	26.9	25.8	28.5	25.8	24.6
$STR_{residential}/STR$	1.16	1.12	1.21	1.15	1.14	1.19

4 Conclusions

- Experimental results for shear strength and slip modulus were obtained for notched and screwed connections between CLT and concrete. The notched connection with a depth equal to the layer thickness, resulted in a 90% higher shear strength and 237% higher slip modulus than screwed connections.
- The experimental value of slip modulus for screwed connections was 50% higher than that proposed by the draft of the new Eurocode 5 for timber-concrete-composites.
- A simply supported CLT-concrete-composite pedestrian bridge was designed considering two different connection types experimentally studied.

- The notched connections showed a better performance than screwed connections in the bridge structural design, with a span over thickness ratio 4-5% higher for the same number of CLT layers.
- The structural design was limited by the serviceability limit state for 5 layers CLT, and by ultimate limit state for 9 layers CLT.
- This slab bridge typology made from CLT-concrete-composite shows a better structural yield for lower thicknesses. When increasing the bridge span, the material volume decreases its efficiency, thus, it is advisable to change the bridge typology, such as beams and concrete slab.
- Future works will include different notches depth and vibration studies in the CLT-concrete-composite, as well as different bridge typology performances.

Acknowledgments

This research project has been sponsored by the Projects: i) SOE4/P1/E1115 «Eguralt: Application and dissemination of innovative solutions for the promotion of mid-rise timber construction in the SUDOE area», co-financed by FEDER funds within the framework of the Interreg SUDOE program; and ii) 04/18/PA/0010 MEDGON: Design and development of a mixed wood-concrete industrialized construction system for high-rise buildings, funded by *Instituto para la Competitividad Empresarial de Castilla y León* in the call 2018 *PROYECTOS DE I+D.*

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