Journal of Building Engineering 32 (2020) 101725

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: http://www.elsevier.com/locate/jobe

# Experimental evaluation of a modular timber unit filled with insulated corkboard

Caroline D. Aquino [a], Jorge M. Branco [b,*]

[a] Federal University of Santa Catarina, Florianópolis, Brazil
[b] ISISE University of Minho, Guimarães, Portugal

ARTICLE INFO

*Keywords:*
Timber structures
Modular construction
Prefabrication
Sustainability

ABSTRACT

Due to fast delivery and convenience on site, prefabricated modular structures are increasingly present in the context of civil construction. Regarding the advantages of these systems, it has been addressed in the literature the potential of wood for the design of prefabricated houses with modular characteristics, resulting in optimization of costs, product quality and sustainability. When a new construction system is proposed, it is of extremely importance to understand its mechanical behavior and structural performance before its implementation. Therefore, this research aims to contribute, based on an experimental campaign, to the characterization of a new modular wall construction system made of Cryptomeria wood (*Cryptomeria japonica*). The experimental campaign comprehended the evaluation of the glued connection between wood elements of the unit and the load carrying capacity of a single and connected modular units. Besides, since the proposed system is constituted of an interior layer of insulated corkboard, the effect of its presence in mechanical terms was evaluated. The results showed the potential of this prefabricated modular systems in terms of resistance and identified the critical parameters to a safety design.

## 1. Introduction

Wood is one of the oldest materials used in construction due to its availability in nature and its relative ease of handling [1]. From prehistory to the 19th century, the most important engineering works were structured with stone, wood, or through their combination. It was only in the industrial revolution that it was possible to produce other materials in enough quantity to replace wood in buildings [2].

In Europe, one of the first forms of construction of wooden houses is construction with overlapping tree trunks with carved corners. There are records of log houses arranged horizontally or vertically, however, the horizontal arrangement of the logs provided greater stability to the construction, therefore, it had greater application [3]. From the 15th century, with the evolution of technological development, log houses were replaced by board houses or rectangular logs. In the late Middle Ages, buildings of up to 5 and 6 floors were built, many of which resisted as much or more than those built in stone and bricks [4].

The technological development of the wood industry has led to the appearance and improvement of construction systems, as well as the emergence of new products derived from wood. The increase in the potential for using this material caused the industrialization of the construction of wooden houses and consequently, the emergence of new production processes [5]. Beyond that, the increase of the use of timber in structural engineering is motivated in the context of sustainability, since wood has distinctive environmental benefits compared with other building materials [6].

Prefabrication arises as an alternative to provide a construction system that combines resistance, quick assembly on site, with a competitive technical differential and, above all, commitment to the environment. Modular houses are usually constructions that rely on prefabricated materials and elements with modular capacity. Thus, modular timber elements rationalize the design and construction of buildings, which makes it possible to increase the degree of industrialization, while maintaining some freedom in terms of architectural design [7,8].

Regarding the advantages of these prefabricated systems, Branco [5] draws attention to the different types of modular wooden construction, referring to the potential of wood for the design of prefabricated houses with modular characteristics. The author highlights that the optimization of work resulted of this type of construction systems consequently results in a reduction of the construction overall cost. In terms of the system quality, Johnsson and Meiling [9] performed audits on the building process of industrialized housing and concluded that the final

* Corresponding author.
*E-mail addresses:* carolinedapieve@gmail.com (C.D. Aquino), jbranco@civil.uminho.pt (J.M. Branco).

https://doi.org/10.1016/j.jobe.2020.101725
Received 18 May 2020; Received in revised form 27 July 2020; Accepted 16 August 2020
Available online 4 September 2020
2352-7102/

product quality is better than conventional housing.

In this context, a new wall construction system was proposed by the company Rusticasa. The system consists of a modular hollow section element for building walls and foresees the improvement of their thermal behavior through the filling of the hollow section with insulation corkboard (ICB). Besides the thermal advantages, the filling choice consists of a sustainable alternative to the rockwool insulation usually used to fill "load bearing wall" systems. According to Gil [10], ICB is a 100% natural and ecological product, an advantage not matched by the competing material.

The connection design of the introduced building module is based on traditional log-house (LH). In modern constructions, LH consists of squared solid wood logs or laminated beams locked together with single or multiple tongue-and-groove connections that facilitate the assembly and improve the wall stability. The connection between walls is made by self-locking hardware. The proposed system mainly differs from traditional LH construction in the cross-section design of the elements. The first usually consists of rectangular solid wood cross-section while the latter one resort on a hollow-wooden section filled with ICB. And, to ensure an adequate stabilization of the wall, a 6 mm screw every meter, is used to interconnect the logs in height.

To guarantee an acceptable structural safety level, the performance of new structural systems should be well understood before its implementation as a building element. Therefore, this research aims to contribute, based on an experimental campaign, to the characterization of the mechanical behavior of the suggested elements. The experimental campaign comprehended the evaluation of the wood shear strength, the load carrying capacity of the unit, and the connection behavior between two overlapping units. Besides, since the system is constituted of an interior layer of ICB, the effect of its presence in mechanical terms was evaluated. Finally, a simplified analytical modeling is presented to assess the admissible vertical and lateral design loads of the wall system.

## 2. Experimental campaign

The wall construction system proposed consists of individual elements of hollow section, like a trunk, which results from the bonding of four elements of Cryptomeria wood (*Cryptomeria japonica*). This hollow wooden unit is filled with insulation corkboard (ICB) which results in the improvement of the thermal properties (insulation capacity) of the walls and, beyond that, in the reduction of the amount of wood needed. Moreover, the advantages related to the economy of wood adds up to the sustainable benefits obtained by replacing the usual rockwool filling material per ICB. The final solution consists of wooden elements of 40 mm thick glued together, where the typical aspect ratio of the cross-section unit (b/h) is approximately 0.90. The wall construction is materialized by the vertically overlap of the various units by tongues and grooves, the details of the connection are presented in Fig. 1. The stability of the wall is guaranteed, besides the finger joint connection, by a 6 × 240mm screw every meter that joins the logs together.

The experimental campaign has been conducted in the Civil Engineering Department of University of Minho, in Portugal. The experiments were determined considering that the log-walls will be under in-plane compression loads, causing compression and shear stresses to the wood pieces and glued connection that joins the elements to form the units. Therefore, the experimental campaign consisted of the evaluation of the shear strength of the Cryptomeria wood, since the behavior of glued connections is a function of this property [12], and the evaluation of the glued connection itself, to verify its efficiency. Besides, the load-carrying capacity was estimated for two different load situations, the first one with load applied only on the upper wooden element of the unit, and the second one, with load applied to the overall top of the unit. Finally, the behavior and load-carrying capacity of two overlapped units were assessed, and consequently, the performance of the finger joint used to connect two elements was verified. The tests were carried out with and without the ICB filling for comparison purposes.

The specimens were prepared in an industrial environment, by

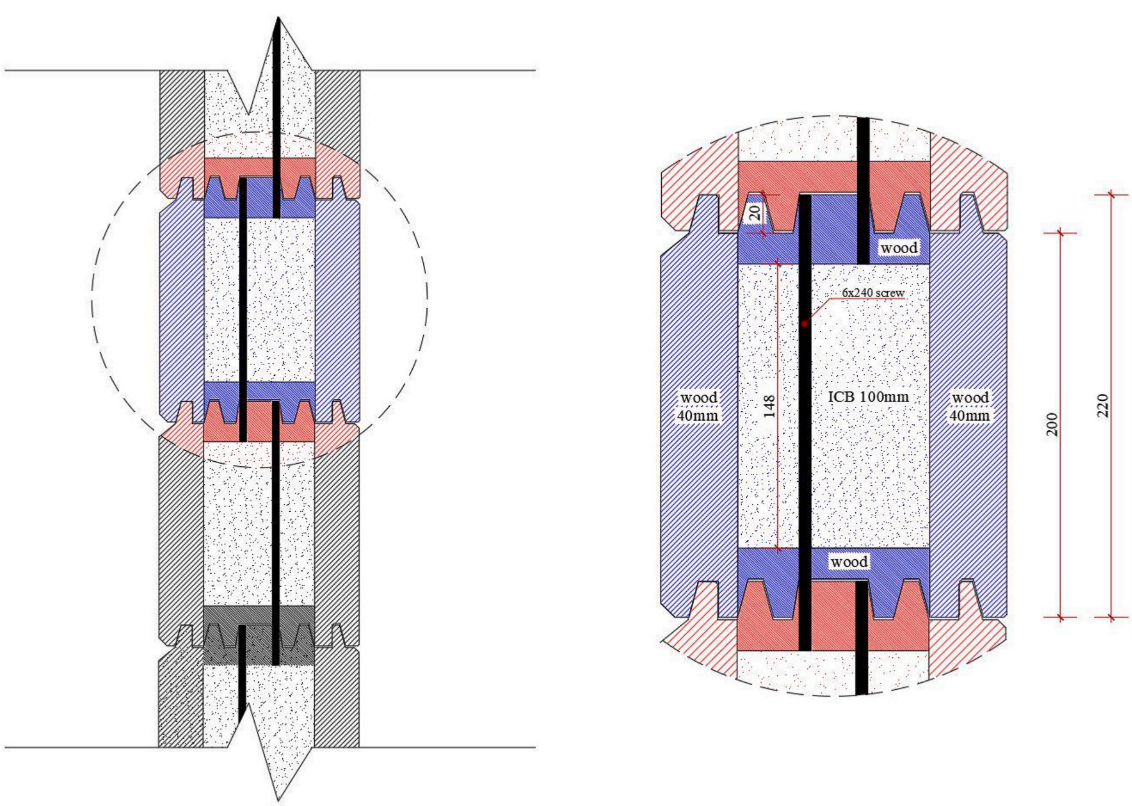



**Fig. 1.** Scheme of the wall cross-section (in millimeters).

Rusticasa industry, and adopting the current methodologies and procedures to produce glued timber elements. After their production, the specimens were transported to the laboratory and kept in a climatic chamber under controlled conditions (T = 20 °C and 65% RH) until their stabilization in accordance to ISO 3130 [13].

With respect to the glue, a Melamine Urea Formaldehyde (MUF) resin system, namely, the MUF 1247/2526 from AkzoNobel, was used. The glue is not sensitive to the laboratory temperature/humidity, since according to Custódio et al. [14], well-designed and well-made joints with any of the normally used structural woodworking adhesives should retain their mechanical properties indefinitely if the wood moisture content stays below approximately 15% and if the temperature remains within the range of human comfort.

### 2.1. Shear strength of the cryptomeria wood

In real design applications, the system will be subjected to in-plane compression loads, causing shear stresses to the wood elements and their glued connections. Hence, the cryptomeria wood shear strength was quantified to verify its capacity. Moreover, this experimental setup is important since the measured parameter is an important mechanical property when evaluating the mechanical behavior of the glued connections between the elements that form the units. The test scheme and the geometry of the pieces followed the guidelines of the ASTM D143 [15] standard. The specimens for this experiment will be referred as SC. A load cell with a maximum loading capacity of 200 kN was used and the experiments were realized with a loading rate of 0.01 mm/s calibrated based on previous researches (e.g. Ref. [16]). In total 10 specimens were analyzed with the geometry outlined in Fig. 2.

### 2.2. Behavior of the glued connection

The glued connection between two wood elements was analyzed through two different experiments. The first test was schematized similarly to the setup presented for the shear strength experiment described above, where the behavior of the glued connection was evaluated through a parallel shear test, according to Annex D of EN 14080 [17]. The geometry is illustrated in Fig. 3, where the specimens are referred as CC.

Besides, for comparison purposes, another shear strength experiment was carried out through the application of a compression force, following the push-out test scheme. This experiment setup was used once it has been successfully implemented in the evaluation of glued connections by Barros [18]. The experiment consisted in the evaluation of 10 specimens, where the geometry and test setup are outlined in Fig. 4. Here, the specimens are referred as ACC.

### 2.3. Load-carrying capacity

The tests to evaluate the system load-carrying capacity to vertical loads are divided in three different experiments, described next. The influence of the incorporation of the insulation corkboard (ICB) inside the wooden unit was verified by carrying out tests with and without the cork filling. The maximum loading capacity of the load cell used is 200 kN and the tests were performed under a loading rate of 0.02 mm/s, ensuring that the maximum force was reached in the range of 180–420 s, as stipulated by EN 408:2010 [19].

The main goal of this phase of the experimental campaign is to assess the resistance and obtain an estimation of the stability behavior of modular elements. Investigations on the assessment of structural stability of timber log-walls under in-plane compression usually resort on full-scale compression experiments [11,20,21]. Given the impossibility of this large-scale tests, the behavior, and the load-carrying capacity of two overlapping units was evaluated through the same experiment setup implemented in the mentioned literature.

#### 2.3.1. Load applied only to the upper wooden element of the unit

The most unfavorable situation in the evaluation of the in-plane load-carrying capacity of the unit is that which includes the application of the load only on the upper wooden element. In this situation, the load-carrying capacity is proportional to the lower value between the shear strength of the upper wooden element and the shear strength of the glued connection. This limit situation is unlikely to occur since in the construction system the transmission of vertical loads will also be resisted through the lateral wooden elements that make up the units. On the other hand, this experiment allows the measurement of the mechanical stability of the unit, and of its glued connections.

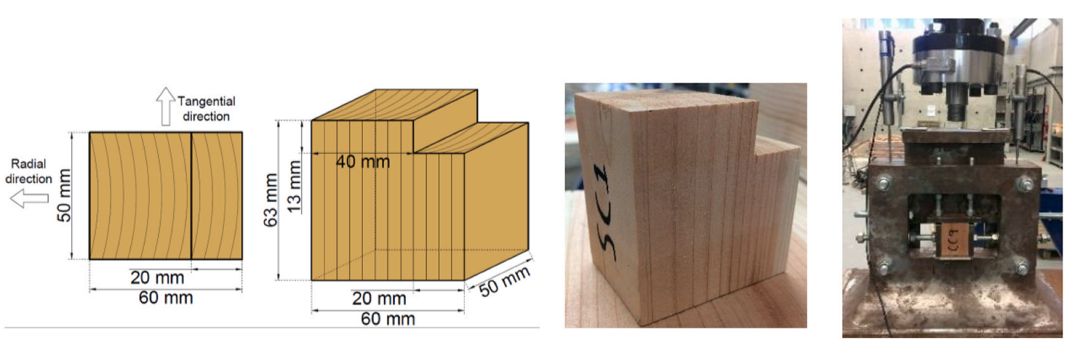
Six test pieces were tested with cork filling, referred as the CP_CC specimens, and without the cork filling, referred as the CP_SC specimens, specified in Fig. 5. The load was applied through a rigid metal bar only on the upper wooden element, as shown in Fig. 6.

#### 2.3.2. Load uniformly applied to the top of the unit

The present specimens consist of the same configuration of the previous ones, the only difference being the area of application of the load. Now, the entire top surface, including the thickness of the two lateral wooden elements that form the unit, is subjected to vertical compression loading. For the application of the load, a rigid bar was used in the whole area of the upper face of the unit (see Fig. 7). Also, in these experiments six test pieces were tested with cork filling, referred as the CD_CC specimens, and without the cork filling, referred as the CD_SC specimens. The geometry properties of the test pieces are the same as given in Fig. 5.

#### 2.3.3. Load uniformly applied on top of two overlapping units

In order to evaluate the performance of the finger joint that connects




(a) (b) (c)

**Fig. 2.** Geometry for the evaluation of the wood shear strength (a) scheme of the geometry (in millimeters), (b) specimen SC, and (c) test setup.

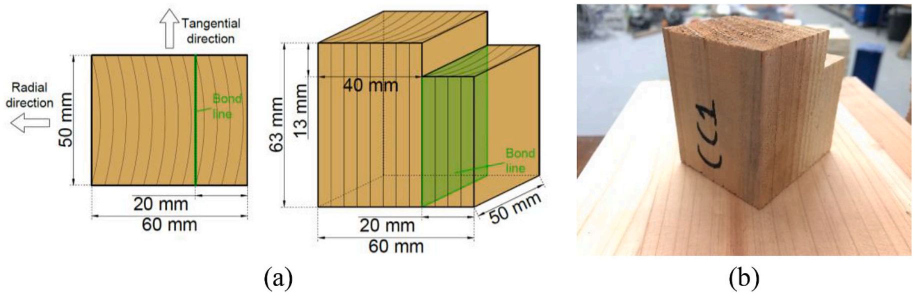



**Fig. 3.** Geometry for the evaluation of the glued connection shear strength (a) scheme of the geometry (in millimeters), and (b) specimen CC.

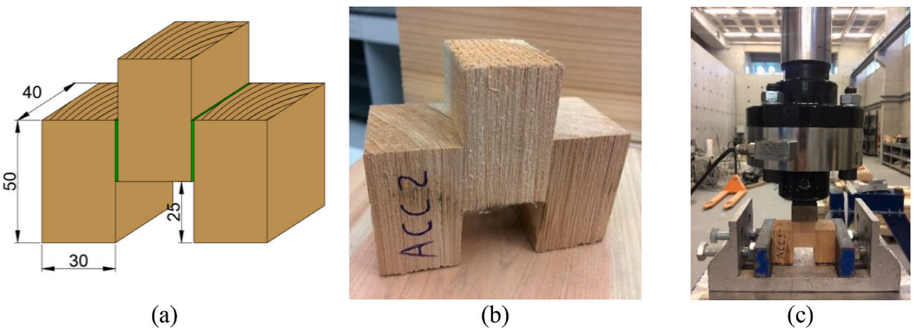



**Fig. 4.** (a) Dimensions of specimens (in millimeters), (b) specimen ACC, and (c) test setup.

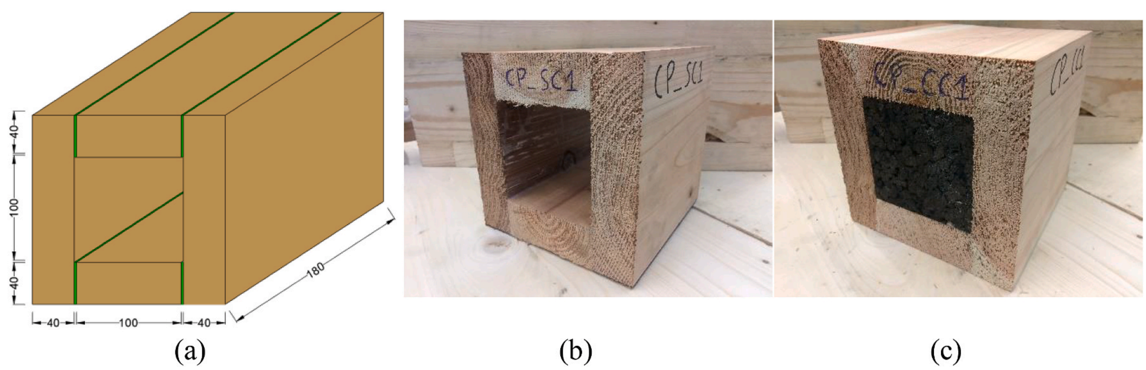



**Fig. 5.** (a) Dimensions of specimens (in millimeters), (b) specimen CP_SC, without ICB, and (c) specimen CP_CC, with ICB inside.

the units to form the wall, test pieces made up of two overlapping units were also tested. As in the previous tests, the influence of filling with cork was also assessed. In this way, 6 specimens without (CD_DSC) and with (CD_DCC) cork were considered. The test setup is similar to the previous one where the load is applied in the entire top surface of the upper unit. Fig. 8 shows the test pieces.

## 3. Results and discussion

The experimental campaign described was carried out to assess the mechanical behavior of the units individually and the global response of the system. The results obtained are presented and discussed for each test performed. Shear and load-carrying capacity experiments are grouped for comparison purposes.

Regarding the shear experiments, it can be seen in the data box plot given in Fig. 9 that the results lead to approximately uniform strength values for the different tests performed. To have a quantitative estimation of the variation between mean strengths results, their relative difference was assessed. Specimens SC and CC, which consisted in the same experimental setup, presented a relative difference of 7.84%. Specimens ACC, however, presented relative differences of 17.23% and 23.65% when compared with the stresses of the SC and CC specimens, respectively. This increase in stress values may result from the setup used for specimens ACC, as the lateral restraining implemented (see Fig. 4) can introduce a prestress level in the glued elements. The typical failure of specimens is illustrated in Fig. 10, similar rupture occurred for all the specimens, with the failure always occurring on the wood side.

From Fig. 9, it can also be observed the difference in variation between the different experiments. The coefficients of variation of specimens were estimated at 11.62% for SC, 19.39% for CC, and 5.97% for ACC. The differences achieved are mainly justified due to the intrinsic variability of wood properties. However, the drastic decrease in variation for specimens ACC may be explained as a result of the lateral restraining implemented in this test setup.

With respect to the load-carrying capacity tests, the results are summarized in a data box plot in Fig. 11. The results for the first two experiments show that almost no structural benefit was obtained by the ICB filling. This conclusion was expected as the registered compression strength of the cork is around 1.2–1.5 MPa [22]. As expected, the results for the experiments referred to the CD_SC and CD_CC specimens

**Fig. 6.** Test setup for the load applied on the upper wooden element.

**Fig. 7.** Test setup for the load applied on the upper wooden element.

presented an increase in resistance compared to the CP_SC and CP_CC specimens. Differently from the single units' experiments, the ICB filling appeared to increase the resistance for this overlapping configuration, presenting an increase of 24.70%, for the experiments regarding the load uniformly applied on top of two overlapping units (specimens CD_DSC and CD_DCC). However, lower resistance values were obtained when compared to the single unit experiments.

As shown in Fig. 12, the failure for specimens CP_SC and CP_CC always occurred in the timber-to-timber connection, in the wood side. This leads to the conclusion that it is the wood strength, shear in this case, that limits the load-carrying capacity of the unit. This is an important conclusion to validate the proposal of the wood hollow section unit as a structural element.

The typical failure observed for specimens CD_SC and CD_CC is shown in Fig. 13. The failure observed is conditioned by the fact that the vertical elements of the hollow section received more load and, therefore, the rupture is influenced by the compression strength perpendicular to the grain of those elements.

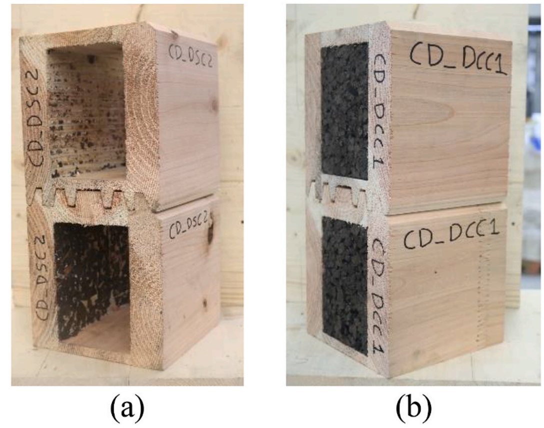



**Fig. 8.** General view of the specimens (a) CD_DSC (without ICB), and (b) CD_DCC (with ICB).

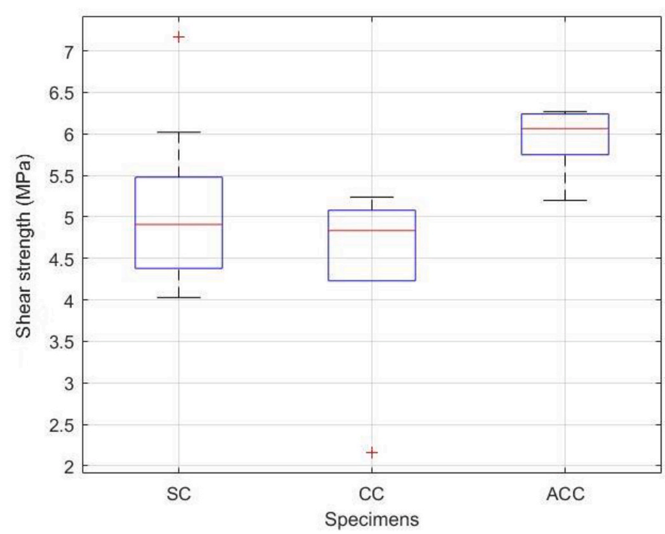



**Fig. 9.** Data box plot of shear experiments.

Finally, typical failures for the experiments with two units overlapped are presents in Fig. 14. In the CD_DSC specimens, a buckling was observed, while in the CD_DCC the failure occurred in the finger joint connecting the elements.

## 4. Simplified analytical modeling

In traditional LH construction, the structural capacity to both vertical and horizontal loads is mainly derived from the interactions and friction mechanisms between horizontal layers of logs. The resistance to vertical loads depends mostly on the compression strength perpendicular to the grain. While horizontal loads are mainly resisted by friction between slots [11,23]. In the experimental campaign, it was observed that, for the new cross-section design proposed, is the shear and compression strength perpendicular to grain that governs the structural capacity of the units to vertical load. In this regard, a simplified analytical modeling is conducted to assess the design permissible service load of the walls in terms of vertical loads and the results are compared to the values obtained in the experimental campaign presented.

In terms of lateral loads, beyond the friction between slots, the structural resistance is guaranteed, as already mentioned, by a 6 × 240mm screw every meter that joins the logs together. The contribution

(a) (b) (c)

**Fig. 10.** Typical shear failure observed during the shear tests performed in (a) wood specimens SC, (b) glued specimens CC, and (c) glued specimens ACC.

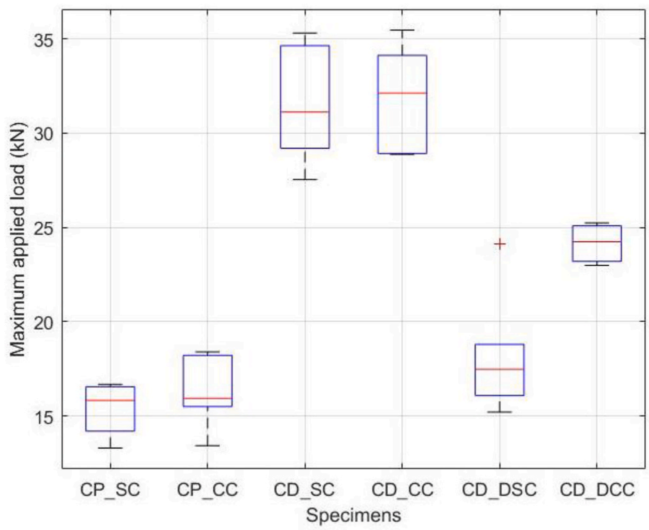


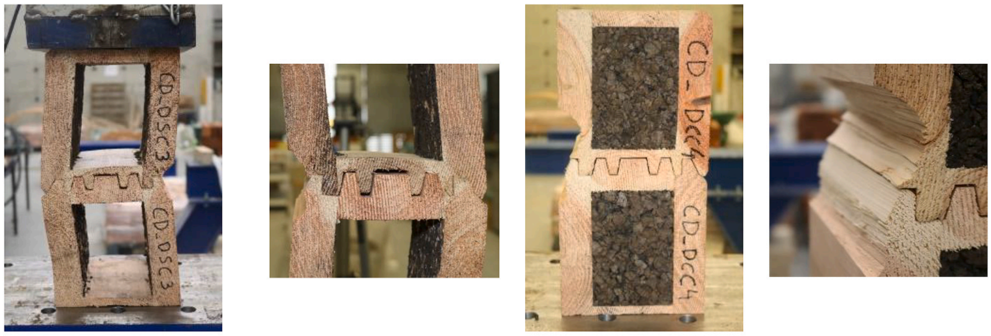

**Fig. 11.** Data box plot of load-carrying capacity experiments.

(a) (b) (c) (d)

**Fig. 12.** Typical failure of specimens (a) CP_SC (without ICB) with (b) detail of the rupture, and (c) CP_CC (with ICB) with (d) respective detail of the failure.

(a) (b) (c) (d)

**Fig. 13.** Typical failure of specimens (a) CD_SC (without ICB) with (b) detail of the rupture, and (c) CD_CC (with ICB) with (d) respective detail of the failure.



(a) (b) (c) (d)

**Fig. 14.** Typical failure of specimens (a) CD_DSC (without ICB) with (b) detail of the rupture, and (c) CD_DCC (with ICB) with (d) respective detail of the failure.

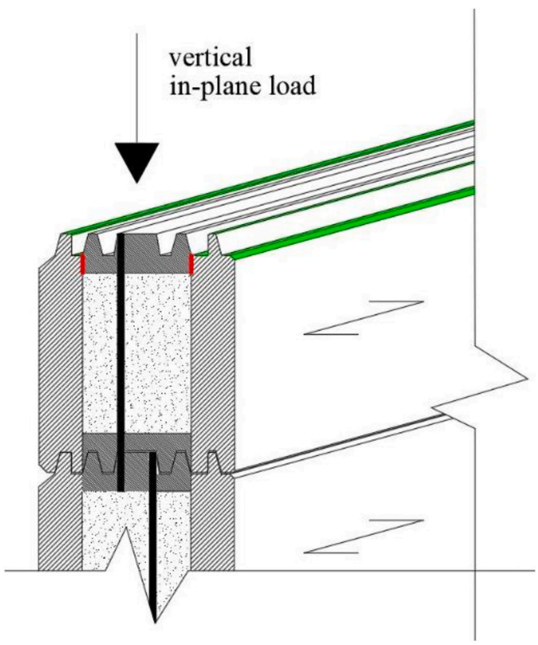



**Fig. 15.** Scheme of the load-carrying mechanism.

**Table 1**
Comparison of the design compression stress perpendicular to the wood fibers recommended by NP 4544:2015 with the experimental values.

| Parameter | Quality Class | |
|---|---|---|
| | CYS II | CYS I |
| Characteristic compression stress perpendicular to the wood fibers $f_{c,90,k}$ | 1.80 | 2.20 |
| Design compression stress perpendicular to the wood fibers $f_{c,90,d}$ | 1.25 | 1.52 |
| Minimum value obtained for $f_{c,90,min}$ (occurred in the CD_DCC tests - with ICB) | 1.60 | |
| Characteristic shear strength $f_{v,k}$ | 3.00 | 3.00 |
| Design shear strength $f_{v,d}$ | 2.07 | 2.07 |
| Minimum value obtained for $f_v$ (occurred in the CC tests) | 2.16 | |

of the screw to the horizontal load-carrying capacity is evaluated according to Eurocode 5 [24] and compared to the resistance obtained by the friction mechanism of the original massive section log system from the same company.

### 4.1. Vertical loads

Regarding the resistance to compressive loads, Fig. 15 indicates the critical regions in the unit of the two-main load-carrying mechanisms: the region in green represents the area where the compression strength perpendicular to grain is most requested, and the region highlighted in red represents the critical shear stress sections.

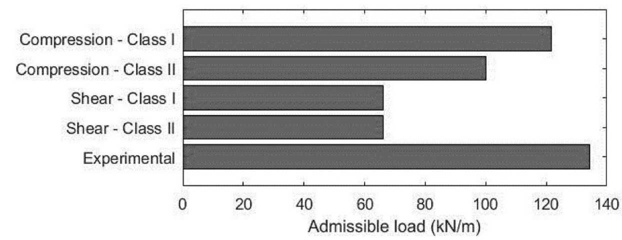



**Fig. 16.** Comparison of design and experimental admissible loads.

The permissible load is estimated in terms of the minimal load-carrying capacity between these two mechanisms, given in Equation (1).

$$F_{adm} = min\begin{cases} A_{comp} \times f_{c,90d} \\ A_{shear} \times f_{v,d} \end{cases} \quad (1)$$

where $F_{adm}$ is the admissible load, $A_{comp}$ and $A_{shear}$ are the respective compression and shear areas given in Fig. 15, $f_{c,90d}$ is the design compression strength perpendicular to grain and, $f_{v,d}$ is the design shear strength.

In terms of design parameters, a comparison is made in Table 1 between the results obtained and the Portuguese standard NP 4544:2015 [25]. The latter one recommends values for the compression and shear strength based on two quality classes of Cryptomeria wood. Based on the results, it can be observed that even the minimum values achieved in the experimental campaign are superior to the design strengths for both quality classes and parameters indicated. The design parameters were calculated according to Eurocode 5 [24], where the strength characteristic values were divided by a partial safety factor of 1.30 and multiplied by a modification factor of 0.90 to account for short-term actions.

It is important to point that the minimum shear strength given in Table 1 is calculated from an outlier value obtained in the CC tests, that is, it may be not representative of the sample. The mean values for shear strength are 4.90 MPa for SC and 5.92 MPa for ACC tests. In this case, it was found that the recommended values given by the Portuguese standard are conservative. However, in the absence of an appropriate experimental characterization, it is highly recommended to use the values suggested by the NP 4544:2015 [25].

Fig. 16 compares the design admissible loads with the mean experimental maximum load obtained in the CD_DCC experiments. Since the loads were obtained for specimens of 180 mm length, the results were extrapolated for meters for comparison purposes. In terms of design, it is the compression mechanism that governs the load-carrying capacity. The experimental maximum load value is greater for both timber classes and mechanisms, guaranteeing a satisfactory safety level (from a range of 9%–50%). The admissible shear loads are the minimum values and, therefore, would govern the design. However, as can be seen in Fig. 16, the experimental maximum load is considerably greater than the admissible design loads and the failure obtained in CD_CDD experiments (see section 3) were all regarded to the compression strength of the pieces. In this context, the admissible loads could be designed in terms of the compression perpendicular to grain failure mode ($f_{c,90,d}$).

Besides the resistant mechanisms mentioned, the buckling behavior is an important property in vertically compressed timber log-walls. Bedon and Fragiacomo [26] conducted a research focused on the assessment of the typical buckling behavior of massive log-walls under in-plane compression. The ultimate buckling load found was superior to the admissible design loads found here. However, it is important to highlight that the cross-section design is different, and, therefore, the critical buckling load could differ between systems. Nonetheless, the proposed system has the advantage of the vertical screws (not existed in the system analyzed by Bedon and Fragiacomo [26]), whose contributions to strength will be evaluated in the next section.

### 4.2. In-plane lateral loads

According to Hirai et al. [27], the lateral resistance mechanisms for log shear walls depends on the interlocks between logs, wood, or steel dowels, vertical through bolts and anchor-bolts, and frictions between logs due to vertical loads. Here the main resistance mechanism is identified as the shear strength introduced in the connection between logs by the screw vertically connecting them. Nonetheless, although not regarded as a resistant mechanism according to Eurocode 5 [24], friction between logs occur in the tongues and groves connection and contributes to the lateral capacity. The friction contribution of a previous wall Rusticasa system, consisted of massive logs, was assessed by Branco and Araújo [11], the investigation lead to the conclusion that considerable friction stresses are developed in the connection between logs, which are function of the vertical pre-compression loads. The conclusion obtained can be extrapolate for the current cross-section as the interlock between the logs is similar. In any case, Hirai et al. [27] argument that the interlocks with notches are too variable to be given definite allowable resistance since their resistance is dependable on vertical loads whose effective values may be periodically dropped by the vertical components of earthquake forces, for example.

To quantify the contribution of the screws, their load-carrying capacity was calculated according to Eurocode 5 [24] guidelines. According to this code, for screws in single shear, the characteristic load-carrying capacity per shear plane per fastener should be taken as the minimum value found from expressions given in (2).

$$F_{v,Rk} = min\begin{cases} f_{h,1,k}t_1 d \\ f_{h,2,k}t_2 d \\ \dfrac{f_{h,1,k}t_1 d}{1+\beta}\left[\sqrt{\beta+2\beta^2\left[1+\dfrac{t_2}{t_1}+\left(\dfrac{t_2}{t_1}\right)^2\right]+\beta^3\left(\dfrac{t_2}{t_1}\right)^2}-\beta\left(1+\dfrac{t_2}{t_1}\right)\right]+\dfrac{F_{ax,Rk}}{4} \\ 1.05\dfrac{f_{h,1,k}t_1 d}{2+\beta}\left[\sqrt{2\beta(1+\beta)+\dfrac{4\beta(2+\beta)M_{y,Rk}}{f_{h,1,k}\ d\ t_1^2}}-\beta\right]+\dfrac{F_{ax,Rk}}{4} \\ 1.05\dfrac{f_{h,1,k}t_2 d}{1+2\beta}\left[\sqrt{2\beta^2(1+\beta)+\dfrac{4\beta(1+2\beta)M_{y,Rk}}{f_{h,1,k}\ d\ t_2^2}}-\beta\right]+\dfrac{F_{ax,Rk}}{4} \\ 1.15\sqrt{\dfrac{2\beta}{1+\beta}2\ M_{y,Rk}f_{h,1,k}\ d}+\dfrac{F_{ax,Rk}}{4} \end{cases} \quad (2)$$

Where $\beta$ is the ratio between the characterisctic embedding strength in timber member 1 $f_{h,1,k}$ and timber member 2 $f_{h,2,k}$; $t_i$ is the timber or board thickness or penetration depth, with i either 1 or 2 (see Fig. 17); $d$ is the fastener diameter; $M_{y,Rk}$ is the fastener yield moment; and $F_{ax,Rk}$ is characterisctic axial withdrawal capacity of the fastener. The embedding strength and the characteristic withdrawal capacity are given by expressions (3) and (4), respectively.

$$f_{h,k} = 0.082\rho_k d^{0.3} \quad (3)$$

$$F_{ax,k,Rk} = \frac{n_{ef} f_{ax,k}\ d\ l_{ef} k_d}{1.2\cos^2\alpha + \sin^2\alpha} \quad (4)$$

where the characteristic wood density.

y $\rho_k$ is adopted according to the recommendations of NP 4544:2015 [25] (312 $kg/m^3$ and 250 $kg/m^3$ for wood class I and II, respectively);$n_{ef}$ is the effective number of screws (not applied here, and therefore taken as unit); $f_{ax,k}$ is the characteristic withdrawal strength perpendicular to grain (in N/mm$^2$); $l_{ef}$ is the penetration length of the screw threaded part; $k_d$is factor given by the minimum between d/8 and unit; and $\alpha$ is the angle between the screw axis and the grain direction (90° in the present design situation).

The screw used in the connections is the TBS screw from Rothoblass® 6 × 240mm. All geometric and mechanical data about the screw were collected in the corresponding technical catalog, namely: $M_{y,Rk}$ = 9493.7N.mm; root and out diameter of 3.95 mm and 6 mm, respectively, leading to an effective diameter of 4.35 mm; and $f_{ax,k}$ = 11.7 N/mm$^2$.

The resulted load-carrying capacity is 1.74 kN for wood class I and 1.57 kN for wood class II per screw per shear plane. For comparison purposes, the load-carrying capacity was also assessed for $t_1$ = 36 mm, and 2.28 kN and 2.07 kN are obtained for wood class I and II, respectively. In both design situations and wood classes, the failure mode (c) was achieved in expressions (2).

Results obtained in Ref. [11] show that the lateral load supported by the friction mechanism of 5 overlapped logs is linear correlated ($y = 0.3389x + 2.2685$ with $R^2$ of 0.9979) with the vertical pre-compression loads. Extrapolating the results, for a vertical service load of 11.31 kN/m (maximum vertical load acting on the walls of the case study in Branco and Araújo [11], this value was adopted since the

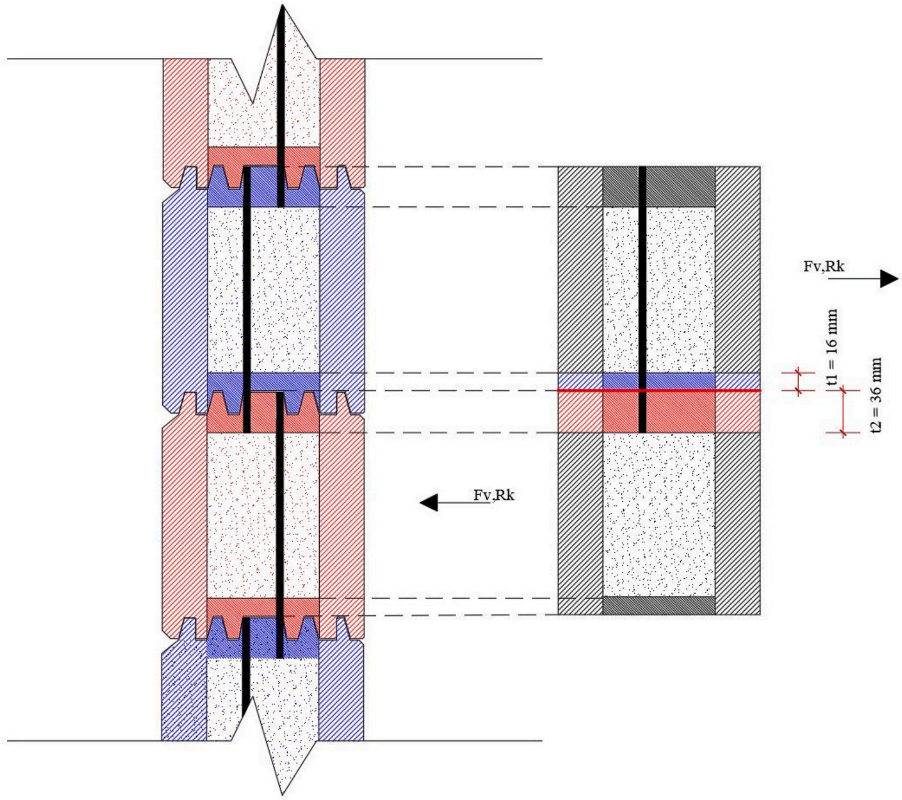



**Fig. 17.** Scheme of the connection in single shear.

architecture of the house is similar, and therefore, so are the loads), the resulted lateral load supported by the system could reach 6.06 kN/m. However, for a design situation the in-plane resistance of log walls is dependable only on the shear resistant mechanism provided by the screws. The lateral load supported by the screws for 5 overlapped logs would be 8.70 kN/m for wood class I and 7.85 kN/m for wood class II, and could reach 11.04 kN/m and 10.35 kN/m with increasing thickness of $t_1$. Here the allowable resistance was calculated by superposing the individual lateral resistance.

## 5. Conclusions

In this research, an experimental campaign aiming to contribute to the characterization of a new wall construction system was conducted. The propose of this system arises in the context of providing an alternative that combines quality structural performance with a quick assembly on the construction site. The experimental campaign comprehended the evaluation of the wood shear strength, the load-carrying capacity, and the mechanical behavior of the unit system. Beyond that, the presence of an interior layer of ICB was evaluated in terms of its structural contribution to the system performance.

The shear strength experiments were carried out to evaluate the wood and the glued connection strength, performed according to the guidelines of ASTM D143 [15] standard, and EN 14080 [17], respectively. The results presented homogeneous values for both parameters, moreover, since the rupture for the glued connection always occurred on the wood side, it can be concluded that the shear strength of the wood governs the connection capacity. Another experiment was performed in terms of the glued connection shear behavior, following the push-out test scheme, the ruptures obtained are similar to the previous one, however, presented greater values for stress. This increase may be resulted from a prestress level in the glued elements due to the lateral restraining implemented in this test setup.

The load-carrying capacity experiments performed on the single units showed that no structural benefit was obtained when adding the ICB interior layer. In the experiments where the load was applied only on the upper element, configuring the worst situation, the rupture occurred on the glued connection. However, when the load was applied in the entire top of the unit, the failure was characterized by the buckling of the lateral timber elements that form the unit.

Regarding the mechanical behavior of two overlapping units, the load-carrying capacity was smaller than the values obtained for the single units' experiments, this is explained because of the presence of the finger joint that connects both elements, weakening the system. Different from the other tests, the ICB filling seemed to increase the structural performance of the wall. A possible reason for this is that the insulation corkboard prevented the buckling failure, observed in the tests without this interior layer, to occur. The failure mode observed on the elements filled with ICB occurred on the finger joint, characterizing the critical point of the system.

Based on the results obtained, a simplified analytical modeling was carried out to assess the vertical and lateral admissible loads of the system. The design compression stress perpendicular to the wood grain proved to be the main design mechanism, and based on the results, the values recommended by NP 4544:2015 [25] could be adopted in the load carrying capacity estimation within an acceptable safety level. Besides, the resistance to lateral loads was assessed by means of the screws lateral load-carrying capacity and compared to the literature.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2020.101725.

## References

[1] W. Pfeil, M. Pfeil, Estruturas de madeira, LTC, Rio de Janeiro, 2003, p. 6.
[2] P.J.C.T.R. Fernandes, A história da madeira como material na arquitectura. Dissertação (Mestrado) – Faculdade de Arquitectura e Artes, Universidade Lusíada de Lisboa, Lisboa, 2014.
[3] S.M. Vaz, Avaliação técnica e económica de casas pré-fabricadas em madeira maciça, 2008. Dissertação (Mestrado) – Faculdade de Engenharia, Universidade do Porto, Porto.
[4] P.B. Lourenço, J.M. Branco, Dos abrigos da pré-história aos edifícios de madeira do século XXI, in: Dissertação (Mestrado) – Departamento de Engenharia Civil, Universidade do Minho, Guimarães, 2012.
[5] J.M. Branco, Casas de madeira. Da tradição aos novos desafios, in: Casas de Madeira, Laboratório Nacional de Engenharia Civil, Lisboa, Portugal, 2013, pp. 75–86 (In Portuguese).
[6] M. Asif, Sustainability of timber, wood and bamboo in construction, in: Sustainability of Construction Materials, Elsevier, 2009, pp. 31–54, https://doi.org/10.1533/9781845695842.31.
[7] D. Gunawardena, P. Mendis, D. Ngo, L. Aye, J. Alfano, Sustainable prefabricated modular buildings, in: 5th International Conference on Sustainable Build Environment, 2014, https://doi.org/10.13140/2.1.4847.3920.
[8] J.C. Molina, C.J. Carlito, Sistema construtivo em "wood frame" para casas de madeira, Semina Ciências Exatas Tecnol. 31.2 (2010) 143–156, https://doi.org/10.5433/1679-0375.2010v31n2p143.
[9] H. Johnsson, J.H. Meiling, Defects in offsite construction: timber module prefabrication, Construct. Manag. Econ. 27 (7) (2009) 667–681, https://doi.org/10.1080/01446190903002797.
[10] L. Gil, Insulation corkboard for sustainable energy and environmental protection, Ciência Tecnol. dos Materiais 25 (1) (2013) 38–41, https://doi.org/10.1016/j.ctmat.2013.12.008.
[11] J.M. Branco, J.P. Araújo, Structural behaviour of log timber walls under lateral in-plane loads, Eng. Struct. 40 (2012) 371–382, https://doi.org/10.1016/j.engstruct.2012.03.004.
[12] G. Tlustochowicz, E. Serrano, R. Steiger, State-of-the-art review on timber connections with glued-in steel rods, Mater. Struct. 44 (5) (2011) 997–1020, https://doi.org/10.1617/s11527-010-9682-9.
[13] ISO 3130, Wood - Determination of Moisture Content for Physical and Mechanical Tests, International Organization for Standardization, 1975.
[14] J. Custódio, J. Broughton, H. Cruz, A review of factors influencing the durability of structural bonded timber joints, Int. J. Adhesion Adhes. 29 (2) (2009) 173–185, https://doi.org/10.1016/j.ijadhadh.2008.03.002.
[15] ASTM D143, Standard Test Methods for Small Clear Specimens of Timber, ASTM International, 2009.
[16] A. Suleimana, Evaluation of the potential of the use of Eucalyptus in the production of glued laminated wood (Glulam) and cross laminated timber (CLT), in: Dissertation (Master Degree) - Civil Engineering Department, University of Minho, Guimarães, 2019.
[17] EN 14080:2013, Timber Structures-Glued Laminated Timber and Glued Solid Timber— Requirements. European committee for standardization, Brussels, Belgium.
[18] B.M.V. Barros, Avaliação experimental de ligações coladas e aparafusadas em estruturas de madeira, Dissertação (Mestrado) – Departamento de Engenharia Civil, Universidade do Minho, Guimarães, 2010.
[19] EN 408:2010, Timber Structures. Structural Timber and Glued Laminated Timber. Determination of Some Physical and Mechanical Properties. BSI, London.
[20] C. Bedon, G. Rinaldin, M. Izzi, M. Fragiacomo, C. Amadio, Assessment of the structural stability of Blockhaus timber log-walls under in-plane compression via full-scale buckling experiments, Construct. Build. Mater. 78 (2015) 474–490, https://doi.org/10.1016/j.conbuildmat.2015.01.049.
[21] P. Grossi, T. Sartori, I. Giongo, R. Tomasi, Analysis of timber log-house construction system via experimental testing and analytical modelling, Construct. Build. Mater. 102 (2016) 1127–1144, https://doi.org/10.1016/j.conbuildmat.2015.10.067.
[22] V. Oliveira, M.E. Rosa, H. Pereira, Variability of the compression properties of cork, Wood Sci. Technol. 48 (5) (2014) 937–948, https://doi.org/10.1007/s00226-014-0651-2.
[23] C. Bedon, M. Fragiacomo, Derivation of buckling design curves via FE modelling for in-plane compressed timber log-walls in accordance with the Eurocode 5, Eur. J. Wood Wood Prod. 75 (3) (2017) 449–465, https://doi.org/10.1007/s00107-016-1083-5.
[24] EN1995-1-1, Eurocode 5: Design of Timber Structures - Part 1-1:general - Common Rules and Rules for Buildings, CEN, Brussels, 2004.
[25] NP 4544, Madeira serrada de criptoméria para estruturas. Classificação visual para fins estruturais, IPQ, Lisboa, 2015.
[26] C. Bedon, M. Fragiacomo, Numerical and analytical assessment of the buckling behaviour of Blockhaus log-walls under in-plane compression, Eng. Struct. 82 (2015) 134–150, https://doi.org/10.1016/j.engstruct.2014.10.033.
[27] T. Hirai, T. Kmiura, K. Yanaga, Y. Sasaki, A. Koizumi, Lateral resistances of log constructions, in: Proceedings of the 8th World Conference on Timber Engineering WCTE, vol. III, Lahti, Finland, 2004, pp. 251–254.