

Optimal log floor patterns

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ABSTRACT

Multi-storey timber constructions predominantly employ engineered wood products as their primary materials. However, these materials undergo extensive processing, including cutting, grading, sorting, planing, and gluing, significantly increasing their cost and environmental impact. An alternative approach to promote the use of timber in construction is to use logs for columns, beams, and floors in buildings, taking advantage of the significant advancements in parametric design and robotics. Nevertheless, it presents specific challenges, such as developing appropriate designs for log connections and establishing protocols for their mechanical characterisation, which are beyond the scope of this research.

The main focus of this article is to conduct a comparative examination of various layout patterns for log floors, aiming to minimise wood consumption and floor thickness. To obtain generalisable conclusions independent of parameters such as wood strength, loads or floor dimensions, an original optimisation method has been developed, inspired by morphological indicators. This article demonstrates that the conventional approach of using parallel joists along the shorter span may not always be advantageous. Instead, it highlights cost-effective solutions that enhance the value of smaller-diameter and shorter logs.

1. Introduction

1.1. General context of engineered wood and log buildings

Timber utilisation in mid- to high-rise buildings has notably increased in recent years. This trend can be attributed to several factors, primarily driven by mitigating anthropogenic climate change [1]. It is worth noting that concrete constructions have, on average, 46 % higher embodied greenhouse gases compared to their timber alternatives [2]. Among the various products employed, adhesive-bonded Engineered Wood Products (EWP) have gained prominence, including Cross-Laminated Timber (CLT), glued-laminated timber (Glulam), and Laminated Veneer Lumber (LVL), presented in Fig. 1. EWP has the benefit of greater size availability and increased strength by averaging defects, making it a preferred choice among engineers. However, their higher embodied energy results from energy-intensive manufacturing processes, particularly when compared to kiln-dried sawn timber, as depicted in Fig. 2 [3]. Moreover, within the processing chain, approximately 50 % of the original log volume is lost as waste [3], and the cut wood grain limits fibre continuity and exposes the knots and other defects [4]. Furthermore, the extensive processing stages significantly

escalate the cost of timber construction.

To address these challenges and promote sustainability and cost-effectiveness in multi-storey buildings, an alternative approach involves utilising natural form whole timber as columns, beams and floor joists, presented in Fig. 3. In addition, natural logs possess superior mechanical properties compared to sawn timber, as the grain continuity mitigates the impact of knots [4]. This advantageous characteristic, coupled with the local availability of logs, has already resulted in their widespread use as piles and utility poles worldwide [5].

In the late 90 s, researchers in Europe and North America [7–10] conducted a broad review of the use of rounded timber for construction. They focused on Small-Diameter Roundwood (SDR), abundantly produced through early harvests to enlarge space for higher potential trees. While SDRs are not suitable for sawn timber due to low saw yield and a high proportion of understrength juvenile wood, it was demonstrated that SDRs could be used as structural elements. As a result, the authors proposed a visual strength-grading standard and destructive testing methods and estimated the load-bearing capacity for various roundwood-steel connections.

Two decades later, Bukauskas et al. [11] conducted a comprehensive review of the current state-of-the-art “whole timber” construction,

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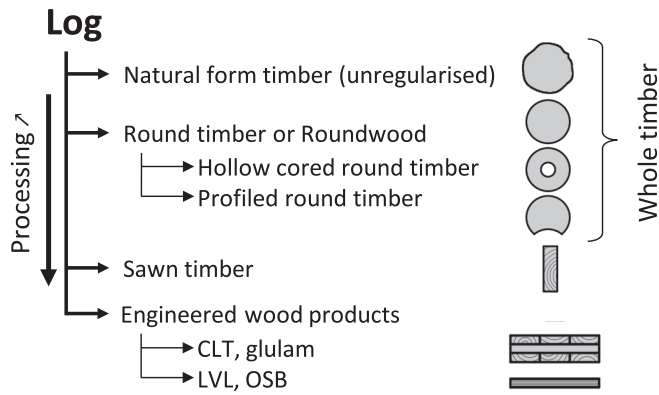


Fig. 1. Timber products from least to most log processing with the typical final section.

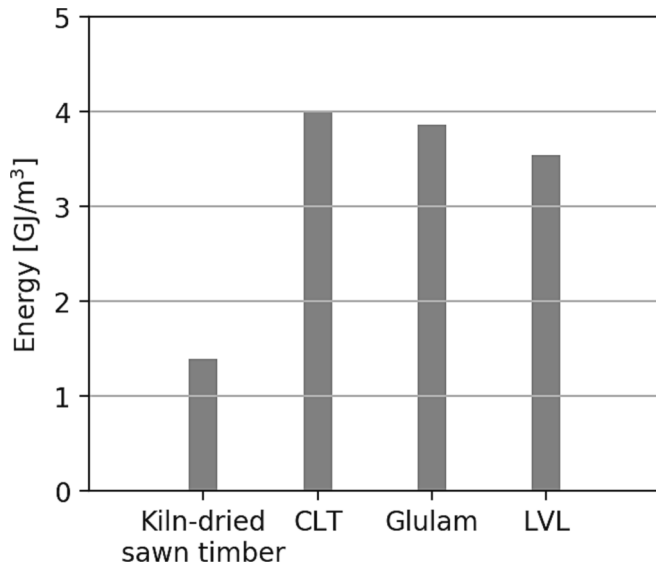


Fig. 2. Total non-renewable primary energy consumption for production (Scope A1-A3), associated with timber products manufactured in the UK. (Values based on [6]).

including natural form and mechanically rounded timber structures. The review emphasises the growing utilisation of rounded timber and highlights the diverse range of potential structural systems involving logs. Additionally, modern 3D scanning tools enable the capture of unique log geometries, facilitating the use of “Form-Fitting” algorithms within parametric design tools [12]. These advancements support architects and engineers in the design process by aligning the log’s geometry with desired specifications. Furthermore, reinforcement techniques are employed to enhance the local strength of log connections [13]. In recent years, the emergence of digital fabrication and robotic arms has opened up new possibilities for innovative wood-wood connections through subtractive fabrication [14,15].

Still, numerous challenges remain for multi-storey log constructions, including adapting building finishes and facades, efficient prefabrication of structures, and selecting non-destructive protocols for the mechanical characterisation of logs. However, the economic and environmental benefits the log structures offer are unquestionable.

1.2. Log floors

In the context of log floors, two key challenges exist. The first arises in meeting building code compliance while establishing suitable connections between logs, and the second deals with the appropriate selection and preparation of logs.

1.2.1. Connecting logs

Logs must be connected longitudinally and transversally. First, longitudinal connections are mainly necessary for connecting joists for a coupling effect, ensuring load redistribution, and attaining sufficient rigidity for efficiently transmitting horizontal forces toward the building core. As depicted in Fig. 4, various practical solutions exist to address this matter: (a) pouring a concrete screed to cover the floor, (b) incorporating transverse steel rebars, or (c) fixing transverse secondary elements or wood-based panels for floor coverage.

Timber-Concrete Composite (TCC) structures provide substantial in-plane and transversal rigidity [16], while the added mass of concrete enhances dynamic behaviour [17]. However, TCC stiffness and strength highly depend on the connection system [18]. Additionally, the concrete compromises this solution’s sustainable attributes and recyclability, and the requirement for metal connectors further escalates the cost.

An alternative approach involves combining logs with prestressed transverse steel rebars or embedded rebar within a non-shrink grout core [19]. However, both methods require direct contact between logs to ensure consistent prestressing and proper grout sealing. Consequently,

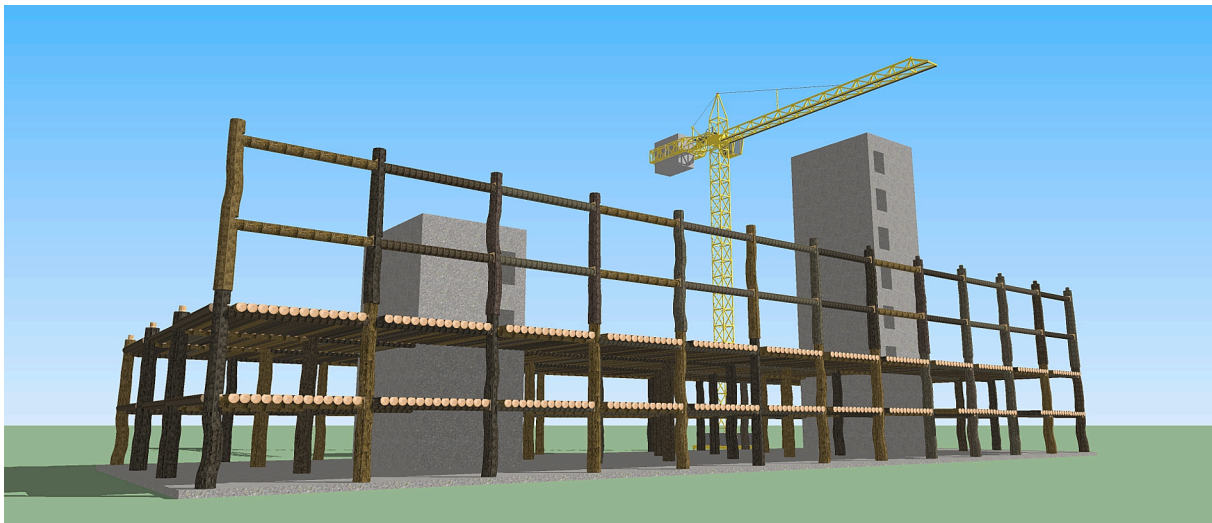


Fig. 3. Possible principle of a mid- to high-rise log structure building.

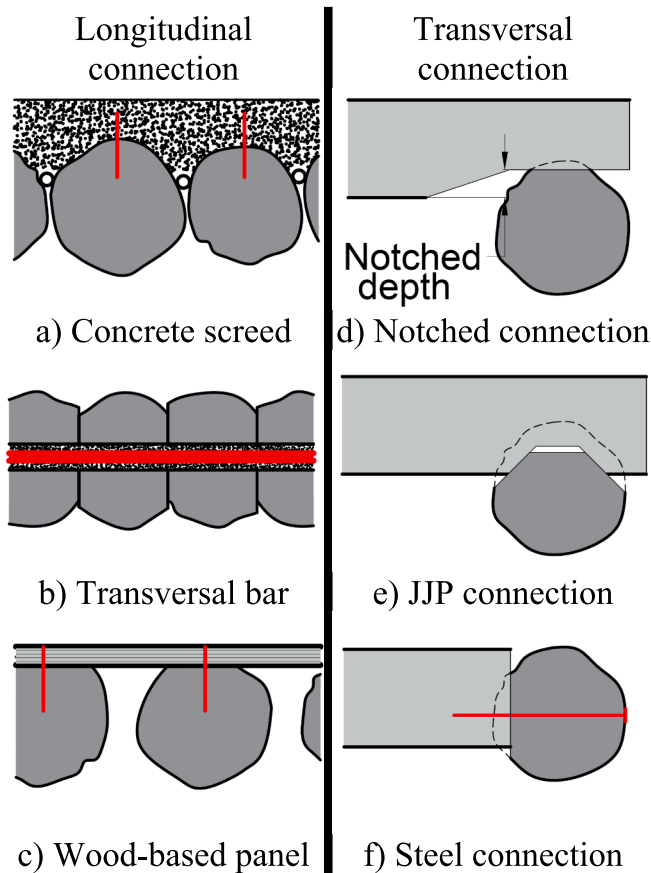


Fig. 4. Several solutions to achieve longitudinal connection between joists and transversal connections between joists and beams.

the logs are positioned side by side with flat surfaces cut on both lateral sides, resulting in increased cutting waste that offsets the advantages of using natural-form timber.

Another option is to employ wood-based panels, such as Oriented Strand Boards (OSB), for connecting log joists. Nonetheless, achieving sufficient connection stiffness is challenging. A noteworthy example of

log flooring can be observed in the Lyss school in Switzerland, where 160 mm diameter silver fir logs were arranged in parallel with a span of 3.3 m, positioned beneath plywood panels [20]. Similarly, Chapman and Dodd [21] employed 200 mm diameter radiata pine roundwood spaced 0.6 m apart for floors of 6 m span (with additional centre support). For fire resistance, their solution included a lower layer of plasterboard and an upper panel composed of two external plywood panels with an inner sand and sawdust mix layer.

Second, many options are available for transversal connections, see illustrations in Fig. 4 (d-f). It should be noted that the connection between floor logs significantly impacts the overall thickness of the floor. On the one hand, numerous examples of historic and modern steel-free connection options exist, as reviewed by Van Nimwegen and Latteur [22]. These steel-free, machine milled solutions are considered more cost-effective as they only require local cutting of the logs. Among them, the simply notched connection (Fig. 4d) and the JJP connection [14] (Fig. 4e) have the benefit of conserving a large portion of the supporting beam in addition to allowing dimensional movements due to moisture variation. On the other hand, steel components can facilitate in-plane connections between logs, thereby reducing the total floor thickness.

To illustrate, Fig. 5 showcases a mock-up natural log floor with a reciprocal pattern made by the authors. The joists, reciprocal framed primary beams, peripheral beams and supports are minimally processed and connected at the same level with self-tapping screws, as presented in Fig. 4f and discussed further in section 4. This design demonstrates the feasibility of employing natural logs in floor construction while preserving their inherent qualities and reducing the need for extensive processing.

1.2.2. Selection and preparation of logs

The selection of wood species influences the logs' expected characteristics and available dimensions (length and diameter). Depending on their intended role in a building design, each log's mechanical and geometrical property assessments may be necessary. Geometrical information can be acquired through manual measurements or advanced techniques such as scanners. Logs with excessive curvature, conicity or spiral grain may be deemed unsuitable for construction. Simultaneously, strength-grading can be carried out with non-destructive methods such as machine testing, dynamic excitation, X-ray scanning, or visual grading, considering factors like growth ring width, knot size, and knot distribution [7].



Fig. 5. Mock-up of a reciprocal log floor 4 m × 4 m, made by the authors (birch wood).

The species of a log can also influence durability. The latter is ensured by preservation and drying to prevent fungal and insect degradation. Therefore, reducing the moisture content of green wood, which is not seasoned or kiln-dried, is mandatory. Green logs building might be feasible if the design allows dimensional variations and post-construction drying. However, failure to meet these conditions necessitates drying to ensure stability and durability. In addition to natural seasoning, artificial drying methods such as kiln drying can expedite the process. Nevertheless, this approach comes with increased costs and embodied energy, as illustrated in Fig. 2, which highly increases with log diameter. The drying process targets a reduction in moisture content to around 12 % at the core to enhance durability and minimise dimensional changes. An intermediate drying solution with higher moisture content is viable, lessening the challenges of using green timber.

1.3. An optimisation method based on Morphological Indicators

Conventionally, architects and engineers design rectangular floors with single-span parallel joists positioned along the shorter span, presuming it to be the most suitable choice. However, the effectiveness of this conventional “classical” solution is not always guaranteed. For instance, Latteur et al. [23] demonstrated that reciprocal log floors are more volume-efficient in particular floor configurations. In addition, Jelusić and Kranja [24] showed that adding primary beams is more cost-effective for the scope of their study. To further investigate alternative patterns with traversal beams, this research conducts a comprehensive comparative analysis, evaluating their performance in terms of volume and thickness: minimising the volume of materials used is crucial to reduce flooring costs, and limiting the floor thickness is essential for achieving buildings with fewer facade surfaces or the potential for additional stories. In addition, adding transversal beams limits the joist’s span and dimensions, allowing the designer to take advantage of SDR.

Determining the overall thickness and volume of a floor requires designing each element following local building codes [25–28], considering five essential design criteria: (i) bending resistance, (ii) shear resistance, (iii) short-term deflection limitation, (iv) long-term deflection limitation, and (v) vibration comfort. These criteria depend on various parameters, such as the dimensions of the rectangular area to be covered, the applied loading, the spacing of the joists, the mechanical properties of timber, and the in-service design parameters for deflection and vibration limitation. For parametric analysis, these continuous and discrete variables significantly increase the computational demands and require precise parameter definition [29].

To address this challenge, this article is inspired by the Morphological Indicator (MI) method [30], which consists of grouping parameters (dimensions, mechanical properties, loads, etc.) into few dimensionless numbers. This approach has never been used before for floors. It enables the expression of a pattern’s minimum thickness or volume solely based on the floor’s width-to-length ratio and the number of joists (both dimensionless numbers). Knowing these two factors at an early design stage enables the comparison between solutions and, therefore, the selection of the most suitable pattern among the proposed alternatives, whatever the project parameters.

The primary objective of this article is first to establish the MI of thickness and volume of different floor patterns and highlight their potential in covering a rectangular area using logs. Subsequently, a comprehensive comparison is conducted to identify the most efficient pattern for achieving optimal results. Finally, based on the findings presented in this paper, general design guidelines are proposed to guide future applications in this field.

2. Method

This section starts by introducing the general assumptions of the case study. Subsequently, the minimum diameter and corresponding volume

required for a single beam are presented, addressing the five design criteria mentioned above. Finally, these results are assembled to establish the MI of total thickness and volume of the proposed floor patterns.

2.1. Assumptions and scope of the study

The assumptions are the following:

- As shown in Fig. 6, two floor support cases are considered: four edge walls (Case 1) or four corner columns (Case 2).

- Floors are composed of primary beams supporting joists. Particular to Case 2, “Peripheral Short Span beams” (PSS beams) and “Peripheral Long Span beams” (PLS beams) need to be added, as specified in Fig. 6.

- The rectangular covered area has a long span of length L_1 and a short span of length $L_2 = \lambda L_1$, with $\lambda \in [0; 1]$ (in practice, values of λ lower than 0.2 are not relevant).

- The joists are spaced with a centre-to-centre distance $e \in [0.25\text{ m}; 0.6\text{ m}]$. Since logs have limited available length ($\in [4\text{ m}; 9\text{ m}]$), L_1/e varies between 5 and 35 but generally equals 20 (for $e = 0.4\text{ m}$ and $L_1 = 8\text{ m}$, for instance).

- Twelve different floor patterns are considered and shown in Figs. 7 and 8. The ten patterns of Fig. 7 differ in joist span direction (X or Y patterns), and the number of bays ($K \in [1; 5]$). The number of joists equals KL_1/e and $\lambda KL_1/e$ for X and Y patterns, respectively. The conventional “classical” solution with single-span parallel joists positioned along the shorter span is denoted as the pattern X1. In addition, two reciprocal framed primary beam patterns (R patterns) are included in the comparison for Case 1 (Fig. 8). These beams primary beams are pinned-jointed together. Based on the results of Latteur et al. [23], patterns R3 and R7 have a rectangle-shaped centre area and, respectively, an engagement ratio α of 0.3 and 0.7, as defined in Fig. 8. These researchers have shown that reciprocal structures with an engagement ratio of about 0.3 are optimal for rectangular floors supported on four walls. In addition, structures with an engagement ratio above 0.7 require exponentially more volume.

- The floor area is loaded with a uniform vertical surface load $q[N/m^2]$ considering self-weight, permanent and variable loading. This load is written q_{ULS} at ultimate loading, and respectively q_{SLS} and $q_{SLS,lt}$ for the short- and long-term service loading. These loadings do not need to be assigned for the MI method. The equivalent total load on the floor is written $F[N] = q \times L_1 \times L_2$ and is written F_{ULS} , F_{SLS} and $F_{SLS,lt}$, respectively. The joists and primary beams are considered loaded uniformly, and peripheral beams are punctually loaded when supporting primary beams.

- The modal mass is expressed as $\eta_{cov} F_{SLS}/g[kg]$, where gravity acceleration is $g[m/s^2]$ and the fraction of the applied mass that vibrates is $\eta_{cov} \in [0; 1]$. η_{cov} depends on the support conditions, the load distribution and the type of loading. For example, the modal mass is expected as half of the permanent and self-weight loads for simply supported beams with a uniformly distributed loading. Furthermore, the vibration interaction between the beams’ layers, joists, and the horizontal rigid decking is neglected.

- The building project specifications impose three in-service performance levels: the maximal relative deflection factor for short- and long-term behaviour (μ_{SLS} and $\mu_{SLS,lt}$, respectively) and the lower bound fundamental vibration frequency ($f_{1,min}[Hz]$). The first two represent the maximal allowable deflection as a fraction of the element’s span, knowing that $\mu_{SLS} \leq \mu_{SLS,lt}$. The lower bound frequency prevents floor resonance of a walker, guarantees occupant comfort and therefore is generally imposed to at least 8 Hz for beams on two supports.

- Connections between logs are considered perfectly hinged, neglecting any rotational and transversal stiffness.

- As presented in Fig. 9, each log is considered as a cylinder of diameter $\phi[m]$ and length $l[m]$ with constant area $A = \phi^2\pi/4$, effective shear area $A_v = 3A/4$, volume $V = A \times l$, moment of inertia $I = \phi^4\pi/64$, and section modulus $W_{el} = \phi^3\pi/32$.

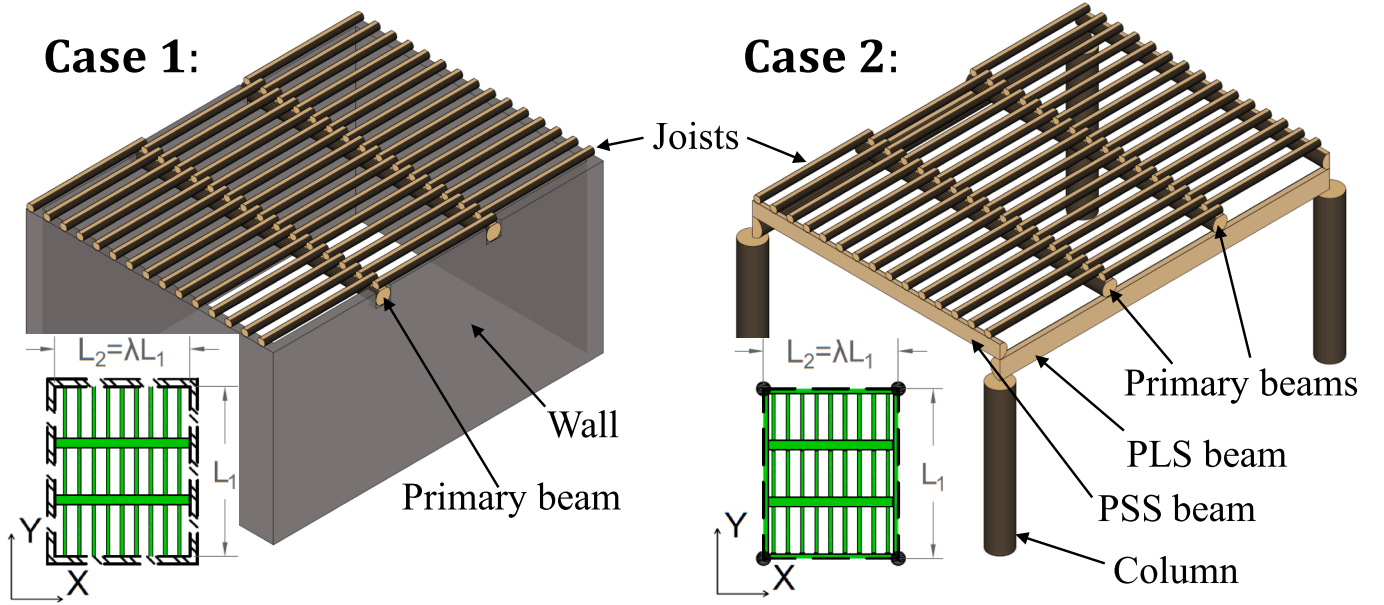


Fig. 6. Y3 pattern with joists, primary beams, peripheral beams and columns.

- The log's mechanical properties are considered known, with a mean longitudinal Young's modulus E , a design bending strength f_b and design shear strength f_v . The latter design strengths include reduction factors that consider timber defects. These properties are identical to all the logs composing the same floor.

- All the floor elements are considered protected from fire.
- Additional assumptions particular to the reciprocal framed floor patterns R3 and R7 can be found in [23].

2.2. Thickness and volume of a single beam

One considers here a single beam, as shown in Fig. 9. Given the coefficient α , β , γ and ε linked to the distribution of the total external load F , one has:

- A maximum ultimate bending moment $M_{ULS}[Nm] = \alpha F_{ULS} l$.
- A maximum ultimate shear force $V_{ULS}[N] = \beta F_{ULS}$. However, since this work focuses mainly on floors, all the beams are supposed to be slender. Therefore, the shear resistance criterion is neglected.
- A maximum service short-term deflection $\delta_{max}[m] = \gamma F_{SLS} l^3 / EI$.
- A maximum service long-term deflection $\delta_{max,Lt}[m] = \gamma F_{SLS,Lt} l^3 / EI$.
- A first service fundamental frequency $f_1[Hz] = \varepsilon \sqrt{EIg / (\eta_{cov} F_{SLS} l^3)}$.

For a uniformly distributed load and self-weight, one has: $\alpha = 1/8$, $\beta = 1/2$, $\gamma = 5/384$ and $\varepsilon = \pi/2$.

Each beam has to respect the five design criteria: bending resistance, shear resistance, short-term deflection limitation, long-term deflection limitation and vibration comfort.

The bending resistance criterion is given by Eqn 1 and leads to the minimum value Eqn 2 and 3 of the beam diameter ϕ_R and volume v_R :

$$\frac{M_{ULS}}{W_{el}} \leq f_b \quad (1)$$

$$\phi_R = \left(\frac{32\alpha}{\pi} \right)^{1/3} \left(\frac{F_{ULS} l}{f_b} \right)^{1/3} \quad (2)$$

$$v_R = l \left(\frac{\pi \phi_R^2}{4} \right) = 3.691 \alpha^{2/3} \left(\frac{F_{ULS} l^{5/2}}{f_b} \right)^{2/3} \quad (3)$$

The short-term deflection limitation criterion is given by Eqn 4 and leads to the minimum value Eqn 5 and 6 of the beam diameter ϕ_S and volume v_S :

$$\frac{\gamma F_{SLS} l^3}{EI} \leq \mu_{SLS} l \quad (4)$$

$$\phi_S = \left(\frac{64\gamma}{\pi} \right)^{1/4} \left(\frac{F_{SLS} l^2}{\mu_{SLS} E} \right)^{1/4} \quad (5)$$

$$v_S = l \left(\frac{\pi \phi_S^2}{4} \right) = \sqrt{4\gamma\pi} \left(\frac{l^2 F_{SLS}^{1/2}}{\mu_{SLS}^{1/2} E^{1/2}} \right) \quad (6)$$

The long-term deflection limitation criterion is adapted from Eqn 4 with force $F_{SLS,Lt}$ and long-term maximal relative displacement factor $\mu_{SLS,Lt}$. Based on the linking parameter $Z_{Lt} = ((F_{SLS,Lt} \mu_{SLS}) / (F_{SLS} \mu_{SLS,Lt}))^{1/4}$, this criterion leads to the minimum value Eqn 7 and 8 of the beam diameter $\phi_{S,Lt}$ and volume $v_{S,Lt}$ parameter:

$$\phi_{S,Lt} = Z_{Lt} \phi_S \quad (7)$$

$$v_{S,Lt} = l \left(\frac{\pi \phi_{S,Lt}^2}{4} \right) = Z_{Lt}^2 v_S \quad (8)$$

When $Z_{Lt} \leq 1$, the short-term deflection limitation criterion is more restrictive than the long-term criterion.

Finally, the vibration comfort criterion, Eqn 9, leads to the minimum value of the element's diameter ϕ_V and volume v_V expressed in Eqn 10 and 11, respectively.

$$\varepsilon \sqrt{\frac{EIg}{\eta_{cov} F_{SLS} l^3}} \geq f_{1,lim} \quad (9)$$

$$\phi_V = \left(\frac{64}{\pi \varepsilon^2} \right)^{1/4} \left(\frac{f_{1,lim}^2 \eta_{cov} F_{SLS} l^3}{Eg} \right)^{1/4} \quad (10)$$

$$v_V = l \left(\frac{\pi \phi_V^2}{4} \right) = \left(\frac{4\pi}{\varepsilon^2} \right)^{1/2} \left(\frac{f_{1,lim}^2 \eta_{cov} F_{SLS} l^5}{Eg} \right)^{1/2} \quad (11)$$

The beam diameter should be the maximum value of all criteria Eqn 2, 5, 7 and 10, while the beam volume should be the maximum value of

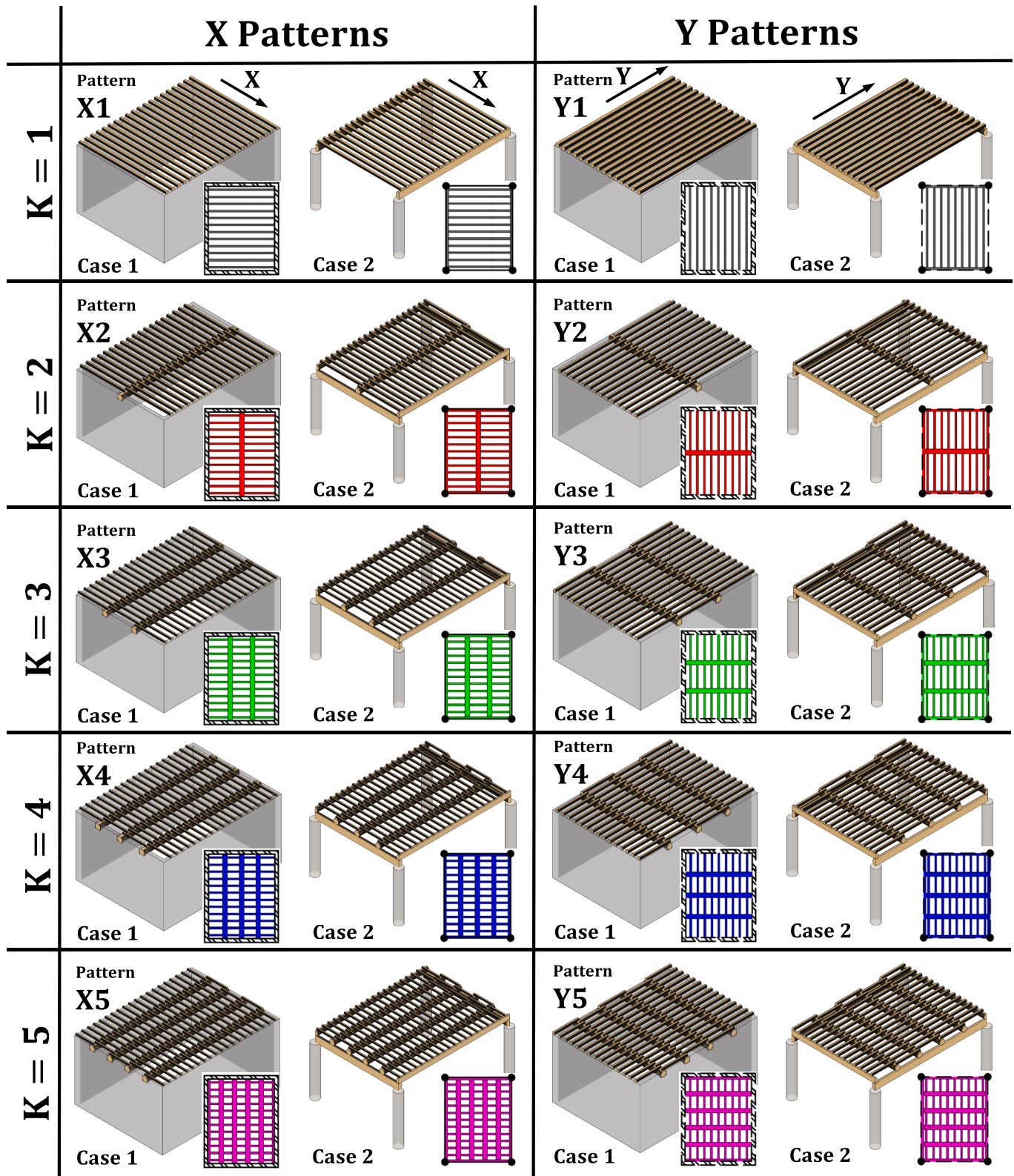


Fig. 7. Ten different floor patterns for Cases 1 and 2, here presented with $\lambda = 0.75$.

all criteria Eqn 3, 6, 8 and 11. However, the long-term design criteria Eqn 7 and 8 are neglected for the rest of this work, assuming that $Z_{lt} \leq 1$. The opposite condition ($Z_{lt} > 1$) occurs when the beam is exposed to high moisture variation (e.g. outside use), and/or when a somewhat restrictive long-term deflection criterion is combined with a rather

weakly restrictive short-term deflection criterion, which is senseless. If this happens, however, the short-term thickness and volume determined in Eqn 5 and 6 must be multiplied by Z_{lt} and Z_{lt}^2 , respectively.

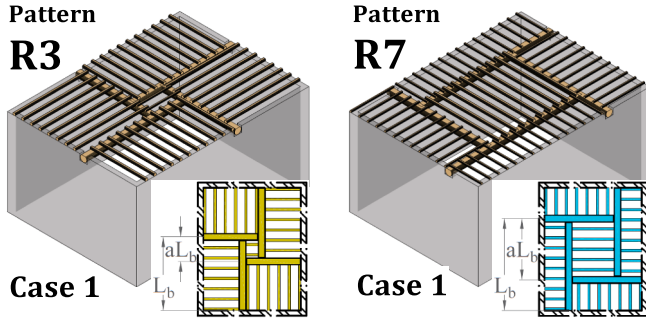


Fig. 8. Two reciprocal patterns with reciprocal framed structures with an engagement ratio a of 0.3 (pattern R3) and 0.7 (pattern R7) of a beam length L_b , here presented with $\lambda = 0.75$.

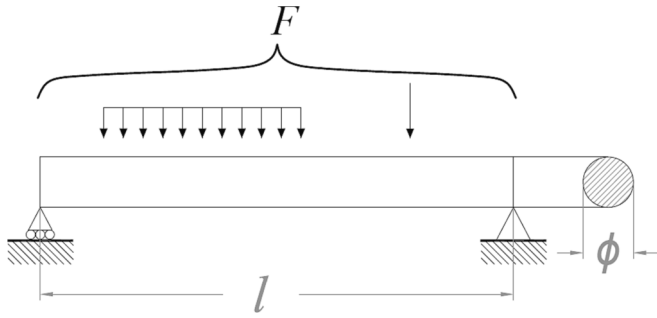


Fig. 9. Simply supported log approximated by a cylindrical beam of diameter ϕ and length l , subjected to total equivalent force F .

2.3. Thickness and volume of a floor

For a floor, the above Eqn 2, 3, 5, 6, 10 and 11 must be adapted to the joists, primary beams, PSS and PLS beams, which:

- Have a length “ l ”, which becomes a function of L_2 , now written $\omega_K L_2$. Values of ω_K are given in Table 1.
- Are loaded by a load “ F ”, which is a function of L_1/e , λ and K . Mathematically, the way to adapt the above equations is to replace parameters α , γ and ε by new parameters α_K , γ_K and ε_K defined in Table 1.
- Are present in a particular number ψ_K , given in Table 1.

These adapted diameters and volumes can then be regrouped to compute the following:

- The total volume of the floor is taken as the sum of all log volumes: $V_{Tot} = \sum (\psi_K^i v^i)$. For Case 1, the total volume regroups the volume of joists and primary beams. For Case 2, the volume of PSS and PLS

Table 1
Values needed to transform the equations of the simple beam to a floor element.

Element	Pattern	ω_K	α_K	γ_K	ε_K	ψ_K
Joist	X	$1/K$	α/ψ_K	γ/ψ_K	$\varepsilon\sqrt{\psi_K}$	$(L_1/e)K$
	Y	$1/(\lambda K)$	α	γ	ε	$(L_1/e)\lambda K$
Primary beam	X	$1/\lambda$	α/K	γ/K	$\varepsilon\sqrt{K}$	$K-1$
	Y	1	α	γ	ε	1*
PSS beam	X	$1/\lambda$	α/K	γ/K	$\varepsilon\sqrt{K}$	1
	Y	1	α	γ	ε	1*
PLS beam	X	1	α	γ	ε	1*
	Y	$1/\lambda$	α/K	γ/K	$\varepsilon\sqrt{K}$	1

* when $K = 1$, $\psi_K = 0$.

beams must be considered in addition to the Case 1's volume. One has:

$$V_{Case 1}^{Tot} = \psi_K^{joist} v^{joist} + \psi_K^{prim. b.} v^{prim. b.} \quad (12a)$$

$$V_{Case 2}^{Tot} = V_{Case 1}^{Tot} + \psi_K^{PSS. b.} v^{PSS. b.} + \psi_K^{PLS b.} v^{PLS b.} \quad (12b)$$

- The total floor thickness is computed as the sum of the diameter of the log multiplied by a reduction factor $\xi \in [0; 1]$: $T^{Tot} = \sum (\xi^i \phi^i)$, with i representing joists, primary beams and peripheral beams, if any. This factor takes in to account the possible cutting at the connection zone (e.g. notch depth) as fraction of the diameter, as presented in Fig. 10 for different options. For Case 1, the total thickness regroups the thickness of joists and primary beams, if any. For Case 2, the thickness of PSS or PLS beams, depending on the pattern, needs to be considered in addition to Case 1's thickness. One has:

$$T_{Case 1}^{Tot} = \begin{cases} \xi^{joist} \phi^{joist}, & K = 1 \\ \xi^{joist} \phi^{joist} + \xi^{prim. b.} \phi^{prim. b.}, & K > 1 \end{cases} \quad (13a)$$

$$T_{Case 2}^{Tot} = \xi^{joist} \phi^{joist} + \begin{cases} \xi^{PLS b.} \phi^{PLS b.}, & \text{patt.X1} \\ \xi^{PSS b.} \phi^{PSS b.}, & \text{patt.Y1} \\ \xi^{PLS b.} \phi^{PLS b.} + \xi^{PSS b.} \phi^{PSS b.}, & \text{else} \end{cases} \quad (13b)$$

The results presented in the following sections will focus only on two first thickness options of Fig. 11: (i) the different types of uncut beams ($\xi^i = 1$) are superimposed on each other (Option 1) or (ii) they are in the same plane (Option 2). However, the next developments of MI are limited to Option 1 and the other options will be discussed in section 4.

2.3.1. Thickness and volume of a floor considering the resistance criterion (bending)

Considering Table 1, the adaptation of Eqn 2 and 3 for any type of floor beam leads to:

$$\phi_R^K(\lambda, L_1/e) = \left(\frac{32\alpha_K \omega_K}{\pi} \right)^{1/3} \left(\frac{F_{ULS} L_2}{f_b} \right)^{1/3} \quad (14)$$

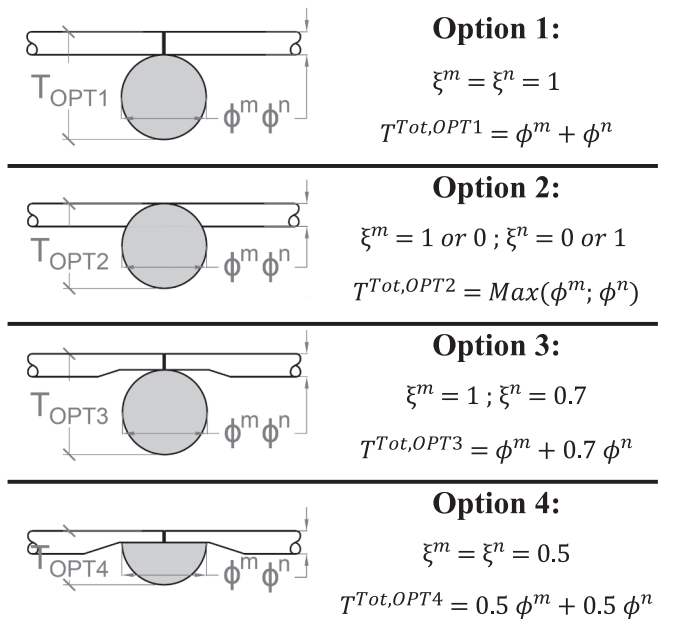


Fig. 10. Different options of floor thickness definition, with m representing primary beams or peripheral beams and n representing joists or primary beams.

$$v_R^K(\lambda, L_1/e) = 3.691(\alpha_K \omega_K^2)^{2/3} \left(\frac{F_{ULS} L_2^{5/2}}{f_b} \right)^{2/3} \quad (15)$$

The previous equations lead to the total thickness or volume of the whole floor using Eqn 12a, 12b, 13a and 13b:

$$T_R^{K, Tot} = S_R^{K, Tot}(\lambda, L_1/e, K) \left(\frac{F_{ULS} L_2}{f_b} \right)^{1/3} \quad (16)$$

$$V_R^{K, Tot} = W_R^{K, Tot}(\lambda, L_1/e, K) \left(\frac{F_{ULS} L_2^{5/2}}{f_b} \right)^{2/3} \quad (17)$$

As an example, considering the pattern X3 of Case 1, as presented in Fig. 7, one has:

$$\begin{aligned} - S_{R, Case1}^{X3, Tot, OPT1}(\lambda, L_1/e) &= S_R^{X3, joists}(L_1/e) + S_R^{X3, prim.b.}(\lambda) = 0.521/(L_1/e)^{1/3} + 0.752/\lambda^{1/3}. \\ - W_{R, Case1}^{X3, Tot}(\lambda, L_1/e) &= W_R^{X3, joists}(L_1/e) \psi_K^{joist}(L_1/e) + W_R^{X3, prim.b.}(\lambda) \psi_K^{prim.b.} = 0.213(L_1/e)^{1/3} + 0.887/\lambda^{5/3}. \end{aligned}$$

Eqn 16 and 17 can be respectively rewritten into Eqn 18 and 19, representing the “Thickness indicator under the resistance constraint” $T_R^{K, Tot}$ and the “Volume indicator under the resistance constraint” $V_R^{K, Tot}$, generically called “Morphological Indicators” (MI) [30]:

$$\frac{f_b^{1/3} T_R^{K, Tot}}{F_{ULS}^{1/3} L_2^{1/3}} = S_R^{K, Tot}(\lambda, L_1/e, K) \quad (18)$$

$$\frac{f_b^{2/3} V_R^{K, Tot}}{F_{ULS}^{2/3} L_2^{5/3}} = W_R^{K, Tot}(\lambda, L_1/e, K) \quad (19)$$

The previous equations have a physical meaning: regardless of the material characteristics f_b , the total load F_{ULS} and the span L_2 , and considering only the bending resistance criterion:

- The minimum floor thickness is obtained for the pattern that minimises function $S_R^{K, Tot}$ for a given λ and L_1/e .
- The minimum volume or mass is obtained for the pattern that minimises function $W_R^{K, Tot}$ for a given λ and L_1/e .

2.3.2. Thickness and volume of a floor considering the stiffness criterion (short-term deflection)

Considering Table 1, the adaptation of Eqn 5 and 6 for any floor beam type leads to the following:

$$\phi_S^K(\lambda, L_1/e) = \left(\frac{64\gamma_K \omega_K^2}{\pi} \right)^{1/4} \left(\frac{L_2^2 F_{SLS}}{\mu_{SLS} E} \right)^{1/4} \quad (20)$$

$$v_S^K(\lambda, L_1/e) = (4\pi\gamma_K \omega_K^2)^{1/2} \left(\frac{L_2^4 F_{SLS}}{\mu_{SLS} E} \right)^{1/2} \quad (21)$$

The previous equations, written dimensionless for a whole floor using Eqn 12a, 12b, 13a and 13b, lead respectively to the “Thickness indicator under the stiffness constraint” $S_S^{K, Tot}$ and the “Volume indicator under the stiffness constraint” $W_S^{K, Tot}$:

$$\frac{\mu_{SLS}^{1/4} E^{1/4} T_S}{F_{SLS}^{1/4} L_2^{1/2}} = S_S^{K, Tot}(\lambda, L_1/e, K) \quad (22)$$

$$\frac{\mu_{SLS}^{1/2} E^{1/2} V_S}{F_{SLS}^{1/2} L_2^2} = W_S^{K, Tot}(\lambda, L_1/e, K) \quad (23)$$

Eqn 22 and 23 have a physical meaning: regardless of the material characteristic E , the total load F_{SLS} , in-service parameter μ_{SLS} and the span L_2 , and considering only the short-term deflection limitation

criterion:

- The minimum floor thickness is obtained for the pattern that minimises function $S_S^{K, Tot}$ for a given λ and L_1/e .
- The minimum volume or mass is obtained for the pattern that minimises function $W_S^{K, Tot}$ for a given λ and L_1/e .

For the previous example, considering the pattern X3 of Case 1, one has:

$$\begin{aligned} - S_{S, Case1}^{X3, Tot, OPT1}(\lambda, L_1/e) &= 0.315/(L_1/e)^{1/4} + 0.546/\lambda^{1/2} \\ - W_{S, Case1}^{X3, Tot}(\lambda, L_1/e) &= 0.078(L_1/e)^{1/2} + 0.467/\lambda^2 \end{aligned}$$

2.3.3. Thickness and volume of a floor considering the vibration criterion (vibration/comfort)

Considering Table 1 the adaptation of Eqn 10 and 11 for any type of floor beam leads to:

$$\phi_V^K(\lambda, L_1/e) = \left(\frac{64\omega_K^3}{\pi e_K^2} \right)^{1/4} \left(\frac{f_{1,lim}^2 \eta_{cov} L_2^3 F_{SLS}}{Eg} \right)^{1/4} \quad (24)$$

$$v_V^K(\lambda, L_1/e) = \left(\frac{4\pi\omega_K^5}{e_K^2} \right)^{1/2} \left(\frac{f_{1,lim}^2 \eta_{cov} L_2^5 F_{SLS}}{Eg} \right)^{1/2} \quad (25)$$

Again, the previous equations, written dimensionless for a whole floor using Eqn 12a, 12b, 13a and 13b, lead respectively to the “Thickness indicator under the vibration constraint” $S_V^{K, Tot}$ and the “Volume indicator under the vibration constraint” $W_V^{K, Tot}$:

$$\frac{E^{1/4} g^{1/4} T_V^{K, Tot}}{f_{1,lim}^{1/2} \eta_{cov}^{1/4} L_2^{3/4} F_{SLS}^{1/4}} = S_V^{K, Tot}(\lambda, L_1/e, K) \quad (26)$$

$$\frac{E^{1/2} g^{1/2} V_V^{K, Tot}}{f_{1,lim}^{1/2} \eta_{cov}^{1/2} L_2^{5/2} F_{SLS}^{1/2}} = W_V^{K, Tot}(\lambda, L_1/e, K) \quad (27)$$

Eqn 26 and 27 have a physical meaning: regardless of the material characteristic E , the total co-vibration mass $F_{SLS} \eta_{cov}/g$, in-service parameter $f_{1,lim}$ and the span L_2 , and considering only the vibration comfort criterion:

- The minimum floor thickness is obtained for the pattern that minimises function $S_V^{K, Tot}$ for a given λ and L_1/e .
- The minimum volume or mass is obtained for the pattern that minimises function $W_V^{K, Tot}$ for a given λ and L_1/e .

As an example, considering the pattern X3 of Case 1, one has:

$$\begin{aligned} - S_{V, Case1}^{X3, Tot, OPT1}(\lambda, L_1/e) &= 0.565/(L_1/e)^{1/4} + 1.288/\lambda^{3/4} \\ - W_{V, Case1}^{X3, Tot}(\lambda, L_1/e) &= 0.25(L_1/e)^{1/2} + 2.606/\lambda^{5/2} \end{aligned}$$

3. Results

The mathematical expressions of the MIs for the resistance, stiffness, and vibration constraints demonstrate that they cannot be directly compared with each other. However, they can be utilised individually as design tools in the early design stage or for conducting comparative analyses, considering one criterion at a time and independently of the other two.

3.1. Designing tool in the early design stage

This sub-chapter explains how MIs can be used for fast decision at the early design stage, based on a $8m \times 8m$ square floor supported by walls (Case 1) with a required joist spacing of 400 mm. Fig. 11 provides thickness and volume indicators for Case 1, considering the stiffness constraint (Eqn 22 and 23). The indicators' values are computed as a

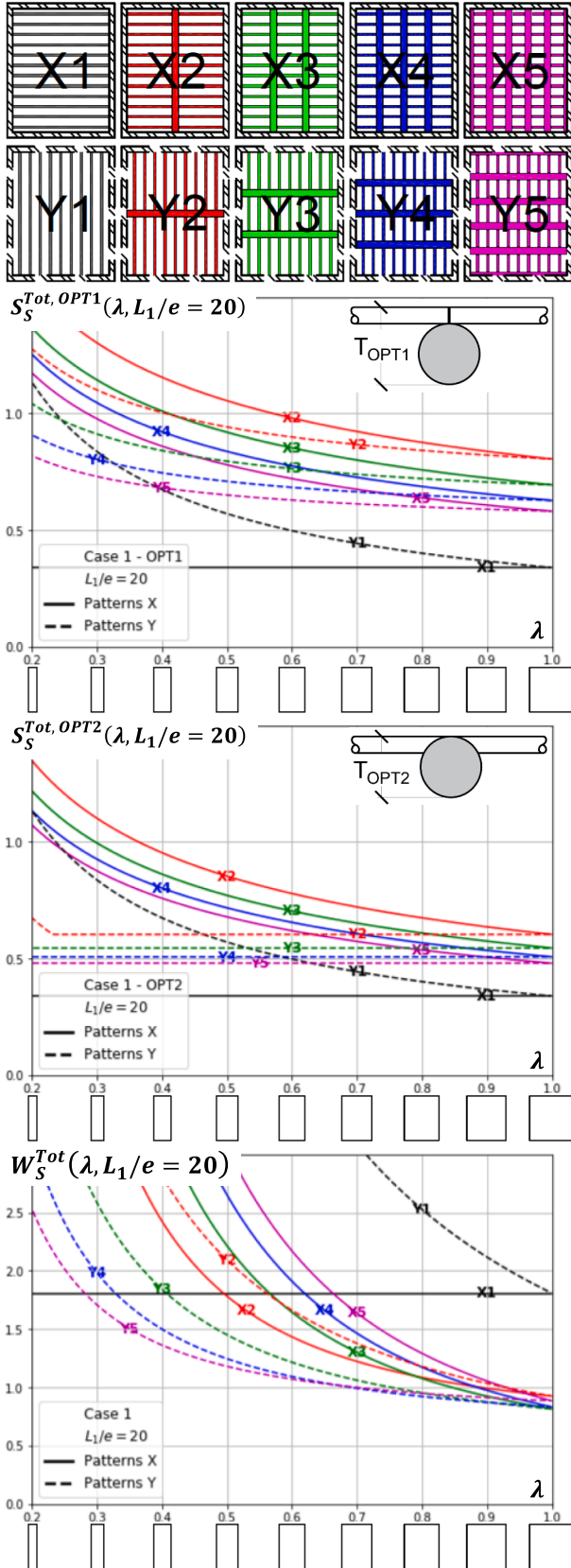


Fig. 11. For Case 1 and $L_1/e = 20$, (from top to bottom) the total MI of thickness of Option 1, thickness of Option 2 and volume under the stiffness constraint; valid for any F_{SLS} , L_2 , μ_{SLS} and E .

function of the floor shape factor λ on the horizontal axis and fixed number of joists $L_1/e = 20$.

Based on the observations from Fig. 11, the following conclusions can be drawn regarding the floor thickness for both options:

- The “classical” pattern X1 consistently emerges as the best solution for both options, irrespective of the floor’s shape λ . This pattern remains a horizontal line since its parameters ω_K , α_K and ν_K are independent of λ , as detailed in Table 1.
- Pattern X2 consistently performs significantly worse than other solutions.
- In general, patterns X2 and Y2 respectively yield greater thickness compared to the other X and Y patterns that have a higher number of primary beams ($K \geq 3$). For example, when compared to patterns X1 and Y1 for $\lambda = 1$, they result in 2.37 times more thickness for Option 1 and 1.78 for Option 2.

And regarding the floor’s volume:

- Expectedly, pattern Y1 is never a good solution.
- For small values of the floor’s shape factor λ , the minimum volume is obtained with the “classical” pattern X1.
- Compared to pattern X1, significant volume gains can be obtained by considering patterns Y3, Y4, and Y5, which reduce the volume by up to 55 %, 54 %, and 51 % respectively for $\lambda = 1$.

For the given situation, if thickness is not a major concern (Option 1), the optimal solution is patterns X3 or Y3, as $\lambda = 1$, minimising the volume of material. The indicator of thickness and volume can be respectively computed as follows: $S_{S, Case 1}^{X3, Tot, OPT1}(\lambda, L_1/e) = 0.315/(L_1/e)^{1/4} + 0.546/\lambda^{1/2} = 0.696$ and $W_{S, Case 1}^{X3, Tot}(\lambda, L_1/e) = 0.078(L_1/e)^{1/2} + 0.467/\lambda^2 = 0.816$.

Considering a uniformly distributed service loading q_{SLS} of 5 kN/m² (including variable, permanent and self-weight load), a mean Young modulus E of 11,000 MPa for all the logs, and a maximal relative short-term displacement factor μ_{SLS} assumed to be 1/350 of each log’s span, the total thickness of Option 1 can be calculated as:

$$T_S = S_{S, Case 1}^{X3, Tot, OPT1} \frac{F_{SLS}^{1/4} L_2^{1/2}}{\mu_{SLS} E^{1/4}} = 0.696 \frac{(5 \times 64 \times 10^3)^{1/4} 8000^{1/2}}{(1/350)^{1/4} 11000^{1/4}} = 625 \text{ mm}$$

The total volume can be calculated as:

$$V_S = W_{S, Case 1}^{X3, Tot} \frac{F_{SLS}^{1/2} L_2^2}{\mu_{SLS} E^{1/2}} = 0.816 \frac{(5 \times 64 \times 10^3)^{1/2} 8000^2}{(1/350)^{1/2} 11000^{1/2}} = 5.3 \times 10^9 \text{ mm}^3$$

It is important to note that these results can be easily recalculated for different loading conditions and mechanical properties by adjusting the relevant parameters.

3.2. Generalisation

The comparative analysis that was previously conducted is further extended and presented in Fig. 12 (for Case 1) and Fig. 13 (for Case 2). These figures provide the values of the thickness and volume indicators for all the patterns and are subdivided into 18 graphs, labelled from A to R, as indicated in Table 2. The previous example corresponds to the graphs B, H, and N.

Each graph in Figs. 12 and 13 represents the thickness and the volume indicator, with the horizontal axis considering either $L_1/e \in [5; 35]$ (and a fixed value $\lambda = 0.75$) or $\lambda \in [0.2; 1]$ (and a fixed value $L_1/e = 20$).

To highlight the loss or gain compared to the “classical” pattern X1, the values of the indicators in Figs. 12 and 13 are divided by the corresponding value associated with pattern X1.

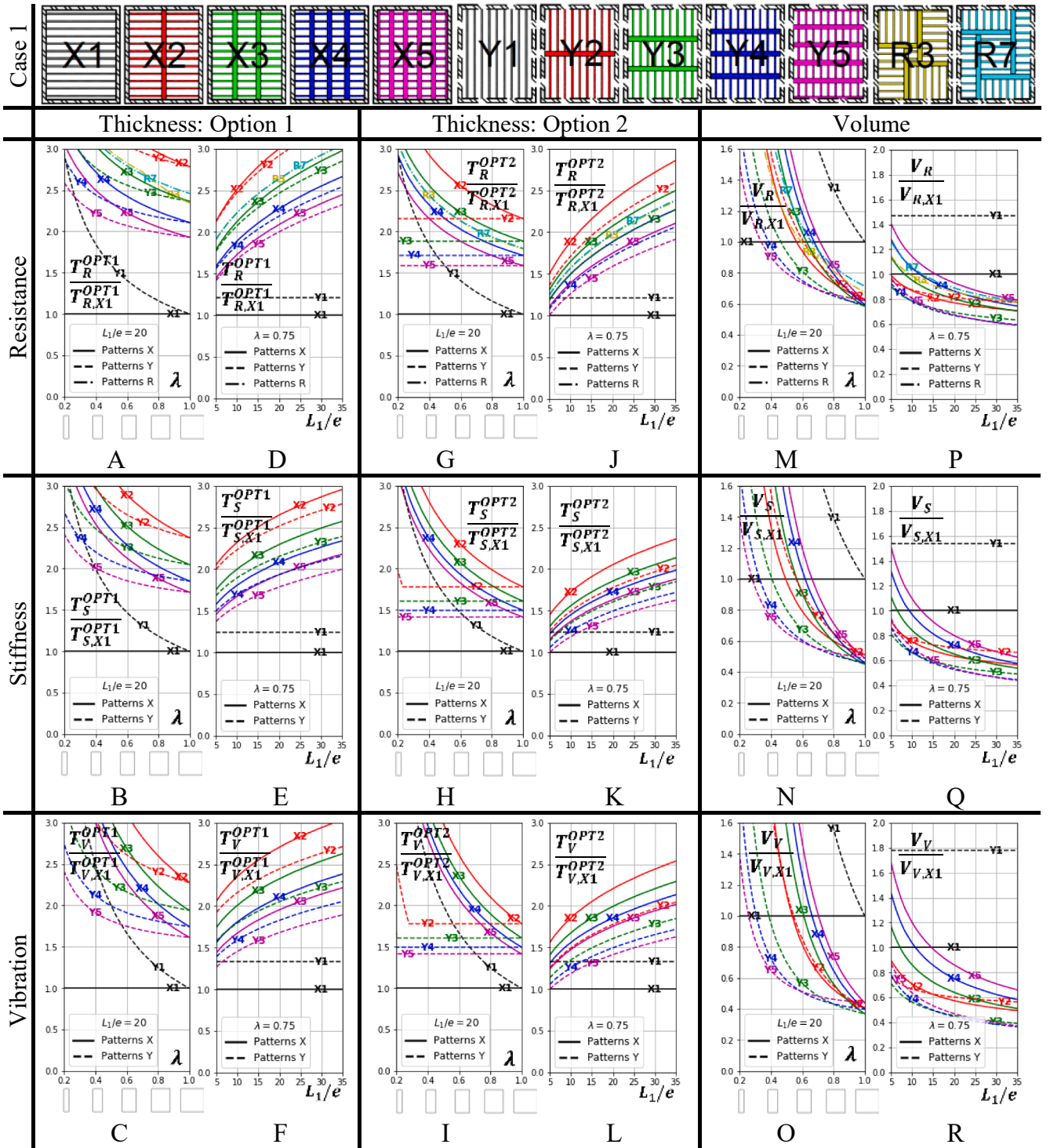


Fig. 12. Relative indicators of thickness and volume (relative to pattern X1) for Case 1.

3.2.1. Case 1: Floor supported by four walls

Regarding **both option's floor thicknesses**, the first two columns of Fig. 12 show that:

- Pattern X1 consistently performs the best among all the options.
- Pattern Y5 is a viable alternative to pattern X1 when aiming to maximize the value of smaller timber elements. For squared floors with few joists, the difference in thickness compared to pattern X1 is minimal. When $\lambda = 1$ and $L_1/e = 20$, pattern Y5 still exhibits 93 %, 71 % and 61 % more thickness for Option 1 but this difference lowers to 59 %, 41 % and 41 % for Option 2 considering the resistance, stiffness and vibration constraints, respectively.

71 % and 61 % more thickness for Option 1 but this difference lowers to 59 %, 41 % and 41 % for Option 2 considering the resistance, stiffness and vibration constraints, respectively.

- Patterns X2 and Y2 are generally the least suitable solution compared to other X and Y patterns.
- Patterns Y2, Y3, Y4 and Y5 consistently have less thickness than their corresponding X patterns with the same number of primary beams.
- Reciprocal patterns R3 and R7 do not offer better results than Y patterns.

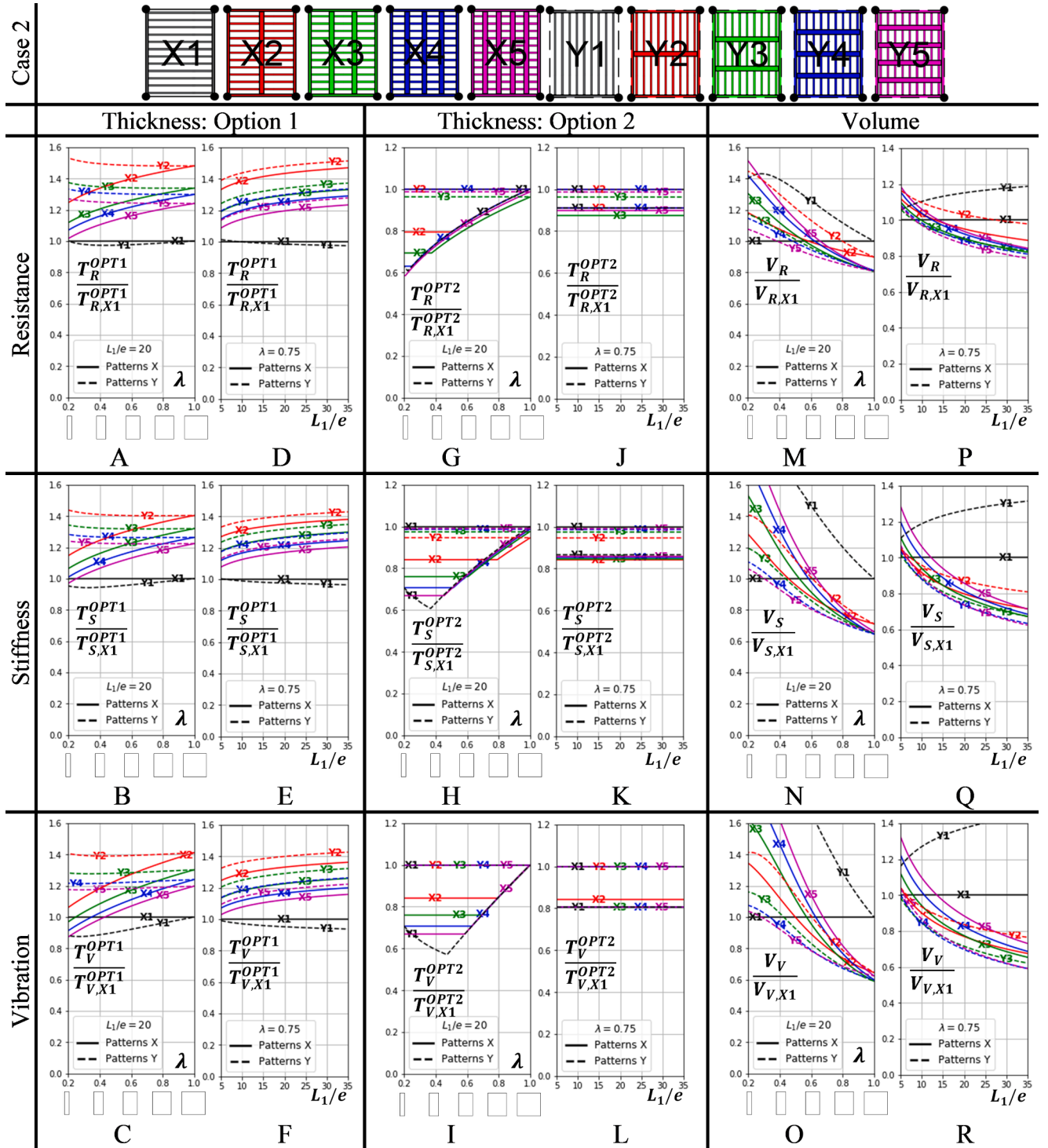


Fig. 13. Relative indicators of thickness and volume (relative to pattern X1) for Case 2.

Regarding the **floor's volume**, the third column of Fig. 12 shows that:

- Pattern X1 is more efficient for smaller shape factors but can become more than twice as heavy as other patterns for more “square” floors ($\lambda \rightarrow 1$).
- Patterns Y3, Y4 and Y5 provide excellent alternatives to pattern X1 and are almost equivalent when $\lambda = 1$, with a gain in volume between 40 % and 60 %, depending on the constraint.

- Pattern R3 is always more efficient than pattern R7, but for nearly squared floors, both patterns are superior to pattern X1, confirming the findings of [23]. However, pattern Y3 is a better solution.

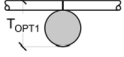
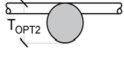
3.2.2. Case 2: Floor supported by corner columns

In Case 2, where peripheral beams are required as shown in Fig. 6, the floor's thickness for Option 1 and Option 2 exhibit distinct behaviour and will be discussed separately.

Regarding the **floor's thickness for Option 1**, the first column of Fig. 13 shows that:

Table 2

Labels of the different graphs depending on the constraint, the compared ratio, the varying parameter and the considered constraint; identical for Case 1 and Case 2.

Variable	Thickness: Option 1		Thickness: Option 2		Volume	
						
	λ	L_1/e	λ	L_1/e	λ	L_1/e
Fixed	L_1/e	λ	L_1/e	λ	L_1/e	λ
Resistance	A	D	G	J	M	P
Stiffness	B	E	H	K	N	Q
Vibration	C	F	I	L	O	R

- The optimal solution for Option 1 is no longer the “classical” pattern X1, but rather the pattern Y1. However, the pattern Y1 only shows a maximum thickness gain of 15 % compared to pattern X1.
- Pattern X5 is the best alternative to patterns X1 or Y1 when aiming to maximize the value of small timber elements. Additionally, its thickness rarely exceeds that of patterns X1 or Y1 by more than 20 %.
- Globally, patterns X2, X3, X4 and X5 are always more efficient than their corresponding Y pattern with the same number of primary beams. An increasing number of primary beams is preferred. Consequently, pattern X2 is always more suitable than other X patterns, and pattern Y2 is consistently the least suitable solution.

Regarding the **floor’s thickness for Option 2**, the second column of Fig. 13 shows that:

- The total thickness is mainly generated by the PSS or PLS beams, which makes the patterns X1, Y2, Y3, Y4 and Y5 highly inefficient.
- Patterns Y1, X2, X3, X4, and X5 are optimal, offering a thickness gain of up to 40 % compared to pattern X1.
- The floor thickness remains constant with respect to L_1/e , except for small value of λ in pattern Y1, where the joists become thicker than the PSS beams.

Regarding the **floor’s volume**, the third column of Fig. 13 shows that for Case 2:

- Pattern X1 is more efficient for smaller shape factors but can become significantly heavier than other patterns for more “square” floors ($\lambda \rightarrow 1$).
- Patterns Y3, Y4, and Y5 provide the best alternatives to pattern X1 and are equivalent when $\lambda = 1$, with a volume gain up to 40 % compared to pattern X1.
- Pattern Y1 is consistently the least suitable solution.

3.2.3. Summary of the results

Fig. 14 summarises the results and presents the order of magnitude of the gain (negative value, e.g. -55 %) or loss (positive value, e.g. +75 %) compared to pattern X1. This order of magnitude is based on the mean value of the results of the different constraint, when $L_1/e = 20$.

Regarding small shape factors ($\lambda \rightarrow 0.2$), the first column of this table shows that:

- **For Case 1**, pattern X1 is consistently better for both thickness options and volume (grey region). Patterns with primary beams consume more volume and have at least 45 % more thickness.
- **For Case 2**, pattern X1 provides a smaller volume. However, patterns Y1, X5, and X4 result in a smaller thickness for both options (white area). Nonetheless, when beams and joists are superimposed, these patterns have almost the same thickness as pattern X1.

Regarding large shape factors ($\lambda \rightarrow 1$), the second column of this table shows that:

- **For Case 1**, pattern X1 is always better for thickness but not for volume (black region: patterns Y3, Y5, and Y4).
- **For Case 2**, pattern X1 exhibits smaller thickness, except for Option 2, where all patterns have almost equivalent thickness. In terms of volume optimisation, patterns with more than 2 primary beams ($K \geq 3$) are the best solutions and provide good alternatives for the use of small logs. For square floors, the volume is minimised when $K = 3$, making it unnecessary to add additional primary beams.

In addition, general remarks can be made:

- Increasing the number of primary beams limits the thickness and volume in all situations. Therefore, dividing the joists’ span only by a factor of 2 ($K = 2$) is not optimal compared to other patterns with more primary beams. Nevertheless, each supplementary primary beam leads to additional connections and on-site installation costs.

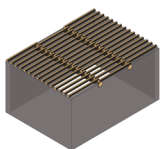
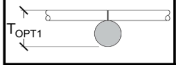
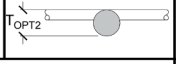
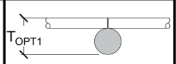
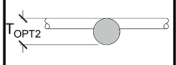
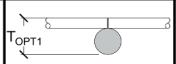
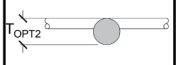
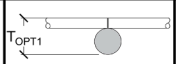
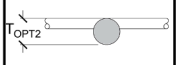
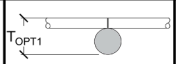
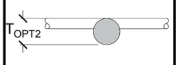
Shape factor			$\lambda \rightarrow 0.2$ 				$\lambda \rightarrow 1$ 			
Case 1 	Thickness		X1	Y5	Y4	Y3	X1	Y5	Y4	Y3
			X1	Y5	Y4	Y3	X1	Y5	Y4	Y3
	Volume		X1	Y5	Y4	Y3	Y3	Y4	Y5	X1
				(+147%)	(+176%)	(+221%)	(+75%)	(+90%)	(+112%)	
Case 2 	Thickness		X1	Y5	Y4	Y3	X1	Y5	Y4	Y3
			X1	Y5	Y4	Y3	X1	Y5	Y4	Y3
	Volume		X1	Y5	Y4	Y3	Y3	Y4	Y5	X1
				(+80%)	(+98%)	(+125%)	(+54%)	(+65%)	(+81%)	
Case 1	Thickness		Y1	X5	X4	X3	X1	X5	X4	X3
			X5	Y1	X4	X3	X2	X1	X5	X4
	Volume		X1	Y5	Y4	Y3	Y3	Y5	Y4	X1
				(-19%)	(-17%)	(-14%)	(-10%)	(+18%)	(+22%)	(+26%)
Case 2	Thickness		Y1	X5	X4	X3	X1	X5	X4	X3
			X5	Y1	X4	X3	X2	X1	X5	X4
	Volume		X1	Y5	Y4	Y3	Y3	Y5	Y4	X1
				(-29%)	(-26%)	(-25%)	(-19%)	(-12%)	(+6%)	(8%)
Case 1	Thickness		Y1	X5	X4	X3	X1	X5	X4	X3
			X5	Y1	X4	X3	X2	X1	X5	X4
	Volume		X1	Y5	Y4	Y3	Y3	Y5	Y4	X1
				(+6%)	(+11%)	(+18%)	(-32%)	(-31%)	(-30%)	

Fig. 14. Review of the observation. Under each pattern, the gain (-) or loss (+) of thickness or volume compared to pattern X1. The highlighted cells show that the pattern X1 (grey), patterns Y3, Y4 & Y5 (black) and patterns Y1, X3, X4 & X5 (white) are minimising thickness or volume.

- Reciprocal framed floors (patterns R3 and R7) do not outperform patterns Y4 and Y5, although they require smaller lengths of logs to cover the same area.
- For Case 2, designers can exclude the additional thickness of the peripheral beams from the total thickness calculation as these dropped beams can be aligned with room partitions, resulting in Case 1's thicknesses.

4. Discussion

This discussion mainly focuses on the connection between floor joists and beams, since they play a significant role in determining the overall thickness of a floor. This section explores the design implications of alternative connection definitions and assesses their feasibility based on construction feedback obtained from the mock-up shown in Fig. 5.

Firstly, Fig. 4 illustrates that the notched connection restricts local cutting to the supporting log, unlike the JJP connection. This characteristic helps to preserve the highly stressed zone of the supporting beam but reduces the potential for thickness reduction. However, the notched connection still affects the resistance to shear at the end of the supported element. As a result, general recommendations limit the notch depth to 15 % of the supported beam's diameter, which can be increased to 30 % when anti-splitter bolts are added [31]. Other codes accept notches up to $\frac{1}{4}$ of the diameter without requiring strengthening measures [32].

This least restrictive recommendation corresponds to thickness Option 3, defined in Fig. 10. In this case, the reduction $\xi^n = 0.7$ need to be applied to the joists' thickness when $K > 1$ for Case 1. Similarly, for Case 2, this reduction factor should be applied to both the joists and the primary beams, if present. When using this thickness option, it is observed that pattern Y5 has at least 55 % more thickness than pattern X1 for Case 1, and 15 % more thickness for Case 2 (vibration constraint). Therefore, notching does not significantly alter the previous observations for both cases, even though the thickness gained by using the pattern X1 is lessened. Additionally, the shear resistance criterion must be adapted to account of the reduced cross-section resulting from notching.

Secondly, in the mock-up floor shown in Fig. 5, the beams and joists are in the same plane, and three connection types are used to achieve this. These connection types are illustrated in Fig. 15:

- Type 1: This connection type involves connecting peripheral beams at the supports. The beams are assembled in the corners with a contact plane cut at a 45° angle, and a notch is made to ensure a good contact surface with the supports. Two self-tapping screws are placed in the logs' axes to secure the connection.
- Type 2: This connection type involves a 50 mm cut-out in the supporting log to create a good contact surface with the end of the supported log. Self-tapping screws are then placed through the supporting beam along the longitudinal axis of the supported beam.
- Type 3: This connection type is used to connect the joists with the primary beams. The ends of the joists are cut at an appropriate angle to match the curvature of the primary beam, ensuring an identical upper floor level throughout. Screws are then placed at both ends of the joists to secure the connection.

While the first connection type (Type 1) was chosen for its ease of fabrication, it has limitations in terms of its application in large-scale buildings due to the inability to achieve vertical column-column connections. However, the second and third connection types (Type 2 and Type 3) can be used in buildings and allow for in-plane connections with minimal processing. Furthermore, these connection types limit cuts to the side of the supporting log, preserving the areas under higher bending stress.

One potential drawback of the second connection type (Type 2) is the presence of gaps between logs, as visible in Fig. 15. These gaps can result from cutting and assembly tolerances as well as hygrometric variations. It is important (i) to ensure that the log moisture content is consistent with the ambient indoor humidity, and adequate knowledge of log geometry is necessary to address these gaps and (ii) to prevent flexure in the screws and mitigate the risk of increased fire damage when exposed to steel parts.

5. Conclusion

Recent developments in parametric design and robotic construction techniques have opened up opportunities for constructing cheaper and more sustainable buildings using minimally processed logs. In particular, this research specifically focuses on the efficient design of log floors and challenges the notion that the "classical" pattern X1, consisting of

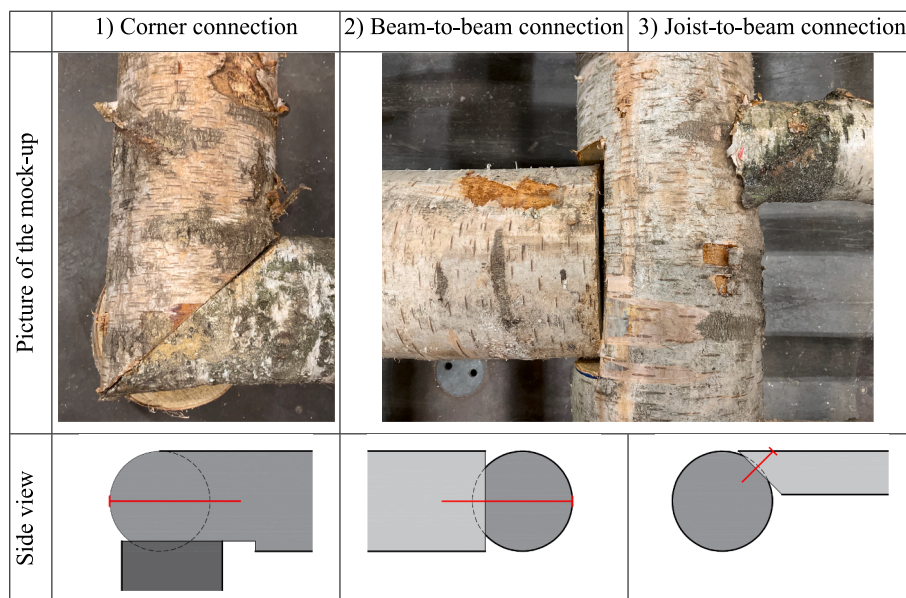


Fig. 15. Connections types for the mock-up floor of Fig. 5.

only joists in the smallest span, is always the best solution. Instead, it highlights the potential benefits of utilising small logs with low market value in alternative patterns.

The Morphological Indicator (MI) method introduced in this study provides a new means to compare and minimise the thickness and volume of different log floor patterns using dimensionless indicators. These indicators offer a universal representation of the floor's thickness and volume, regardless of the material properties (f_b , f_v and E), the loading (F_{ULS} , F_{SLS} and $F_{SLS,Lt}$) and the in-service parameters (μ_{SLS} , $\mu_{SLS,Lt}$ and $f_{1,lim}$). At the early design stage, MIs allow designers to compare, select or reject a floor patterns based on floor dimensions (L_1 and L_2) and joist spacing (e). After, the numerical value of the floor's thickness of volume under a particular criterion can be quickly computed based on the pattern's MI value. Subsequently, the numerical value of the floor's thickness or volume under specific criteria can be quickly computed based on the pattern's MI value.

However, the MI method has limitations as each design criterion is observed separately, disregarding the others. Indeed, the same governing design criterion is supposed for joists and beams, which is not always valid on more complex floors. Additionally, the method does not offer a comprehensive optimisation method that considers multiple parameters simultaneously.

Despite these drawbacks, the MI method still provides valuable insights and a systematic approach to comparing log floor patterns. It can assist designers in making informed decisions by highlighting the

order of magnitude of gain or loss between patterns, in the early design stage.

CRediT authorship contribution statement

Martin Steinmetz: Conceptualization, Methodology, Visualization, Writing – original draft. **Pierre Latteur:** Conceptualization, Writing – review & editing, Supervision. **Luca Sgambi:** Writing – review & editing, Supervision.

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.

Data availability

No data was used for the research described in the article.

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Appendix

The following symbols are used in this work:

Symbols used.

Symbol	Property
a	Engagement ratio
A	Area of the section of a log
A_v	Effective shear area of the section of a log
CLT	Cross-Laminated Timber
e	Centre-to-centre distance between two joists
E	Young's modulus of a log
EWP	Engineered Wood Products
f_1 , $f_{1,lim}$	Fundamental and limited fundamental frequency of a log
f_b	Design bending strength of a log
f_v	Design shear strength of a log
F , F_{SLS} , $F_{SLS,Lt}$, F_{ULS}	Total equivalent force on a floor weighted at short-term service (SLS), long-term service (SLS,Lt) or ultimate (ULS) loading
g	gravity acceleration
Glulam	Glued-laminated timber
I	Inertia of the section of a log
K	Number of bays of a pattern
l	Length of a log
L_1 , L_2	Longest and shortest dimensions of a floor
L_1/e	Number of joists of pattern X1
L_b	Reciprocal framed beam length
LVL	Laminated Veneer Lumber
MI	Morphological Indicator
M_{ULS}	Maximal bending moment at ULS of a log, somewhere
OSB	Oriented Strand Boards
PLS beam	Peripheral Long Span beams
PSS beam	Peripheral Short Span beams
q , q_{SLS} , $q_{SLS,Lt}$, q_{ULS}	Uniformly distributed surface load on the whole floor weighted at short-term service (SLS), long-term service (SLS,Lt) or ultimate (ULS) loading
S_i	Morphological Indicator of thickness of a log or whole floor under the constraint i , depending on λ and L_1/e
SDR	Small-Diameter Roundwood
T_i	Thickness of a whole floor under the constraint i , depending on λ , L_1/e and the considered thickness option
V_i	Volume of a whole floor under the constraint i , depending on λ and L_1/e
W_{el}	Section modulus of a log
W_i	Morphological Indicator of volume of a log or whole floor under the constraint i , depending on λ and L_1/e
X , Y	Shortest and longest direction of the rectangular floor
Z_{Lt}	Linking parameter between short term SLS and long term SLS criteria
α , β , γ , ε , α_K , γ_K , ε_K	Dimensionless factors depending on the position and type of supports and also the distribution of loading and mass on the beam, used of calculating the moment, shear force, vertical displacement and fundamental frequency of a log
δ_{max} , $\delta_{max,Lt}$	Maximal displacement under the short- and long-term service loading of a log, somewhere.

(continued on next page)

(continued)

Symbol	Property
η_{cov}	Proportion of the mass that co-vibrates
λ	Shape factor ($= L_2/L_1$)
$\mu_{SLS}, \mu_{SLS,L1}$	Maximum design value of the vertical displacement, under Q_{SLS} or F_{SLS} and $Q_{SLS,L1}$ or $F_{SLS,L1}$. (for instance, 1/300 or 1/500)
ν_i	Volume of a single log under the constraint i
ξ_i	Reduction factor on the thickness of joists, primary beams and peripheral beams
ψ_K	Particular occurrence of an element in a pattern
ϕ_i	Diameter of the section of a log under the constraint i
ω_K	Dimensionless factor to adapt the length of a single log to the length in floor element

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