

We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

7,000

Open access books available

186,000

International authors and editors

200M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities



WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com



Various Geometric Configuration Proposals for Dovetail Wooden Horizontal Structural Members in Multistory Building Construction

*Hüseyin Emre Ilgin, Markku Karjalainen
and Olli-Paavo Koponen*

Abstract

Adhesives and metal fasteners have an important place in the content of engineered wood products (EWPs). However, adhesives may cause toxic gas emissions due to their petroleum-based nature, while metal fasteners may adversely affect the reusability of these products. These issues also raise important questions about the sustainability and environmental friendliness of EWPs. Thus, there is still room for a solution that is solid and completely pure wood, adhesive- and metal-connectors-free dovetail wood board elements (DWBEs). There are many studies on the technological, ecological, and economic aspects of these products in the literature, but no studies have been conducted to assess the technical performance of DWBEs. This chapter focuses on DWBEs by proposing various geometric configurations for horizontal structural members in multistory building construction through architectural modeling programs. In this architectural design phase, which is one of the first but most important stages, the proposed configurations are based on a theoretical approach, considering contemporary construction practices rather than structural analysis or mechanical simulation. Further research, including technical performance tests, will be undertaken after this critical phase. It is believed that this chapter will contribute to the dissemination of DWBEs for innovative architectural and structural applications, especially in multistory wooden structures construction.

Keywords: timber/wood, dovetail wood board elements, engineered wood products, sustainability, multistory building construction, architectural modeling

1. Introduction

Climate change is dangerously close to spiraling out of control [1, 2]. The probability of this critical phenomenon attributed to human factors is over 90% and requires urgent management of our operations [3]. Buildings are the major contributors to the climate crisis, producing about 40% of annual global CO₂ emissions [4]. Additionally, building operations are responsible for 28% of these total annual emissions, while building materials and construction (often referred to as embedded carbon) are responsible for an additional 11% annually [5].

In this sense, wood as a renewable material is unquestionably ecological and environmentally friendly in terms of low carbon emissions during processing and carbon sequestration: one cubic meter of growing wood can bind about one ton of CO₂ from the atmosphere. If the dry mass of wood is 500 kg, about half of this mass is carbon, namely 250 kg. Thus, timber, which is at the forefront of addressing European climate policy, is considered one of our best allies in resolving climate change, especially due to its environmentally friendly features [6, 7].

Moreover, thanks to its numerous technological benefits such as dimensional stability, uniform strength, ecological properties such as low carbon emission, engineered wood products (e.g., cross-laminated timber, laminated veneer lumber) (**Figure 1**) are increasingly becoming a viable solution in high-rise structures [8–11] as in the cases of the 26 m and 8-story Carbon 12 (Portland, 2018) (**Figure 2**) [12] and the 85 m and 18-story Mjøstårnet (Brumunddal, 2019) (**Figure 3**) [13].

With the standardization of the building industry, adhesives and metal fasteners are often used in engineered wood products (EWPs), replacing traditional wood-to-wood assemblies [14]. It is worth noting here that engineered wood products (EWPs), also called mass timber, composite wood, artificial wood, or fabricated wood, include a range of derivative wood products manufactured by bonding or fastening strips, particles, fibers or wood veneers or boards of wood with adhesives or other fixing methods to generate composite material. Adhesives play a critical role in EWPs, especially by protecting the wood, making the structure light and robust, preventing shrinkage and expansion caused by natural humidity [15, 16], while metal fasteners ensure the overall integrity of the wooden structure [17, 18]. However, adhesives can cause problems in the sustainability and environmental friendliness of EWPs due to toxic gas emissions [19, 20], and similarly, metal fasteners can negatively affect the reusability and recyclability of EWPs [21, 22]. Therefore, there is still room for a solution consisting of solid and completely pure wood, dovetail wood board elements (DWBEs) [23]. Numerous studies have been conducted in the literature on the technological, ecological, and economic aspects of EWPs in construction with different building solutions [24] such as [25–30], and there is limited understating of DWBEs, which mostly includes structural analysis of connection details (e.g., [31–39]). Here, the dovetail wood board elements (DWBEs) can be defined as solid/massive and pure wood structural elements such as floor

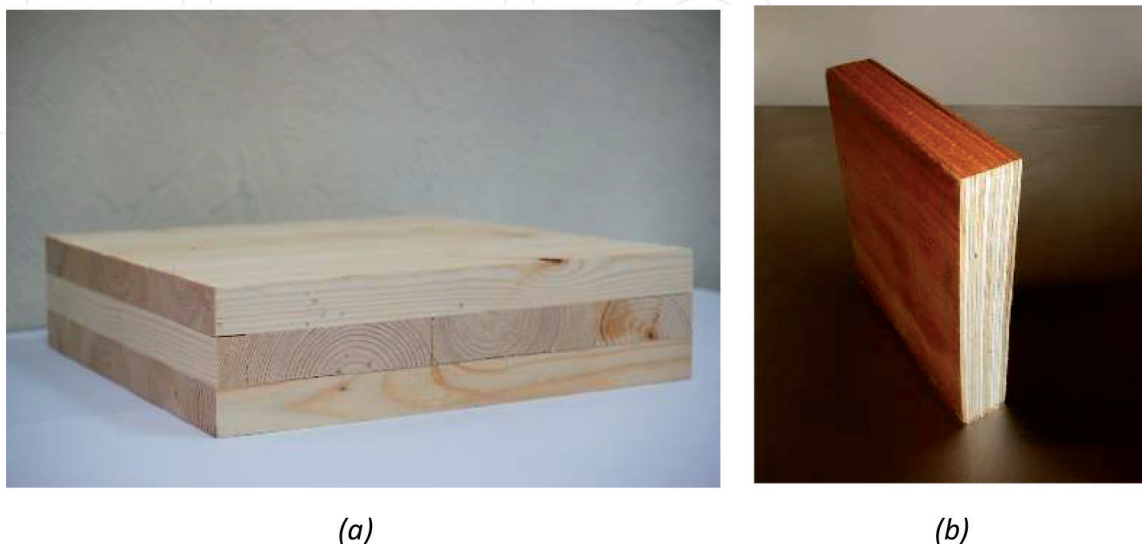


Figure 1. Engineered wood products: (a) cross-laminated timber; (b) laminated veneer lumber (sources: Wikipedia—https://en.wikipedia.org/wiki/Cross-laminated_timber; https://en.wikipedia.org/wiki/Laminated_veneer_lumber).



Figure 2.
Carbon 12 (Portland, 2018) (source: Wikipedia—<https://en.wikipedia.org/wiki/Carbon12>).



Figure 3.
Mjøstårnet (Brumunddal, 2019) (source: Wikipedia—<https://en.wikipedia.org/wiki/Mjøstårnet>).

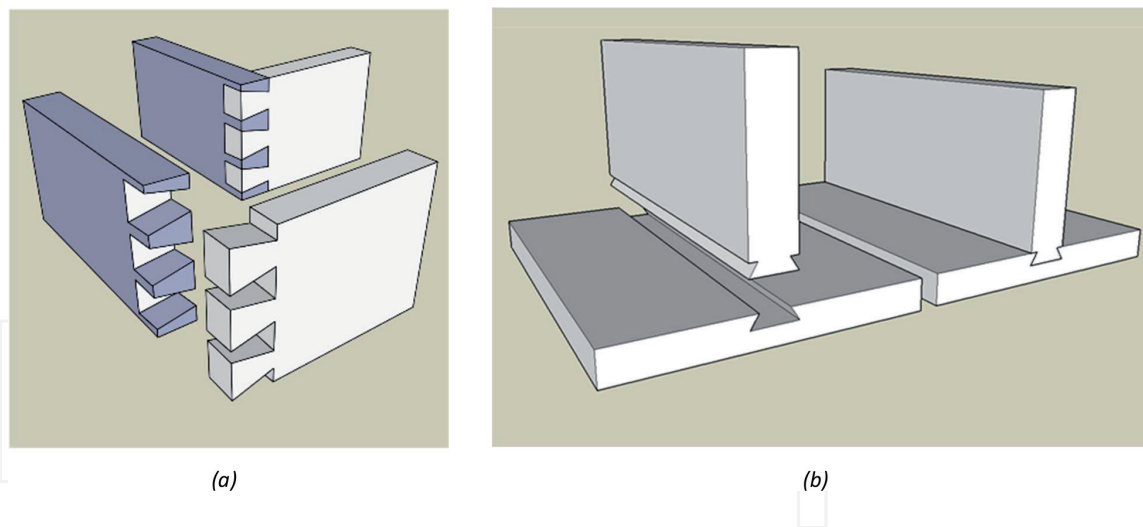


Figure 4. Dovetail joint as one of the oldest joining techniques in furniture design: (a) a through dovetail joint; (b) a sliding dovetail joint (sources: Wikipedia—https://en.wikipedia.org/wiki/Dovetail_joint).

slabs that use plug-in dovetail form in the joint detail and do not use adhesives and metal connections. More importantly, no studies have been conducted to assess the technical performance of DWBEs in multistory construction [40]. This chapter focuses on DWBEs—based on one of the oldest joining methods (**Figure 4**)—as sustainable material alternatives for ecological engineering solutions by suggesting various geometric configurations for flooring of multistory building construction through architectural modeling programs.

It is worth mentioning here that ecological engineering combines contemporary environmental engineering practices with ecological principles to achieve ecologically oriented goals [41–44]. Today, ecological engineering has become an essential tool, with the use of sustainable materials such as wood to tackle challenges resulting from the climate crisis. Given that buildings account for around 40% of annual global CO₂ emissions, the construction of wooden (multistory) buildings, especially with dovetail wooden elements as more environmentally friendly pure wood material, will contribute significantly to the fight against climate change in terms of ecological engineering approach.

It is believed that this chapter will contribute to the creation of higher value-added circular economy opportunities to support European climate policy as part of bio-economy and sustainable development through the dissemination of DWBEs for diverse and innovative structural applications in the construction sector as an ecological engineering-based solution.

In this chapter, wood or timber refers to engineered wood products (EWPs), e.g., cross-laminated timber (CLT—a prefabricated multi-layer EWP, manufactured from at least three layers of boards by gluing their surfaces together with an adhesive under pressure), laminated veneer lumber (LVL—made by bonding together thin vertical softwood veneers with their grain parallel to the longitudinal axis of the section, under heat and pressure), and glue-laminated timber (Glulam—made by gluing together several graded timber laminations with their grain parallel to the longitudinal axis of the section). Moreover, in this research, “multistory building” and “tall building” are defined as a building with over two-story and eight-story, respectively.

2. Research Methods

This study was conducted through an extensive literature survey mainly including international peer-reviewed journals and similar research projects.

Furthermore, this chapter was carried out with architectural modeling methods used in the solution of research and design problems in architectural activities. This method enables architects to think, write, discuss, and disseminate as a bridge from theory to practice [45]. It is widely utilized in architectural design research, where it is used by architects as a tool for research methodology [46, 47].

In addition, currently, there is no single approach to creating the object and subject of architectural activity, which inevitably leads to significant differences in research methods and architectural design of objects, especially at such important

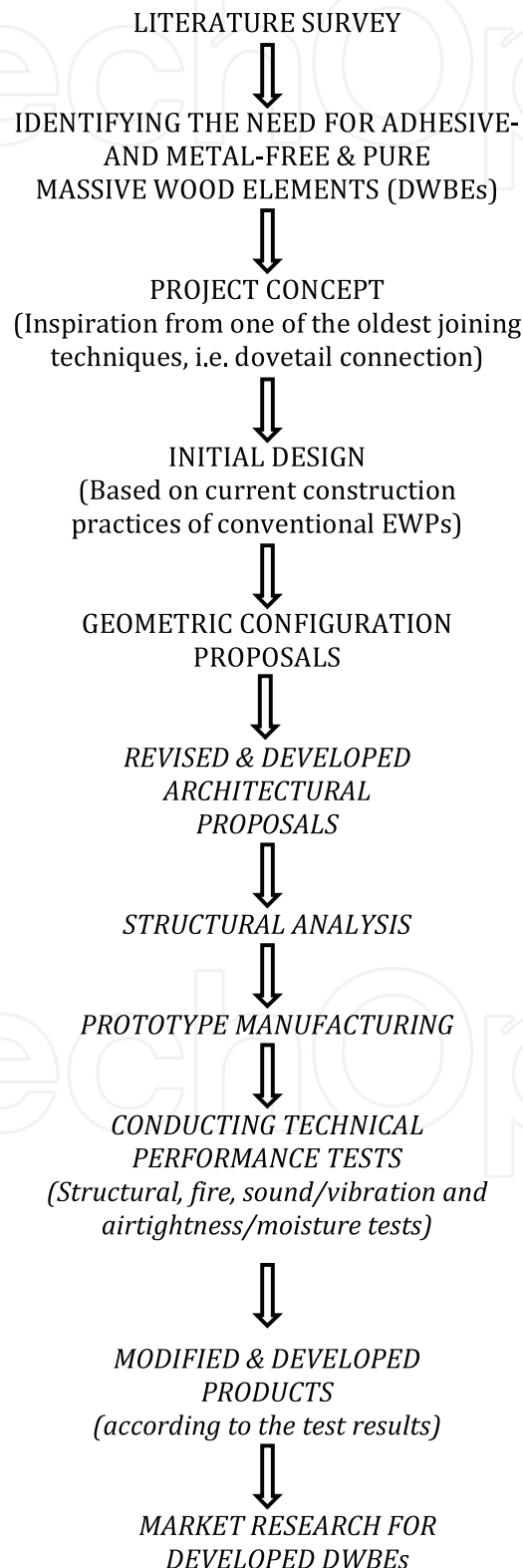


Figure 5. The phases of the preliminary design used as a research method in this study and project's next phases (in italics).

levels of solving this problem [48]. On the other hand, the precise operation of text and project interaction in architectural design research remains a highly debated and relatively unformed topic [49–52].

Hence, main business applications such as AutoCAD, SketchUp, parametric modeling and information modeling methodology of buildings, and complex object modeling methods used in modern architectural design applications (e.g., [53, 54]) were utilized in this study. Here, creative proposals are realized through a mix of drawings and models as visual representations to encourage a fresh and lively approach to architectural research.

Figure 5 shows the phases of the preliminary design used as a research method in this study and the next phases of the project.

3. Findings

DWBE's innovation is based on a new way of combining the understanding of the properties and potential of wood, traditional woodworking skills, mechanical capability to mill large wood boards efficiently and precisely, digital machining control, and digital design. Thus, the architect, structural designer, and production

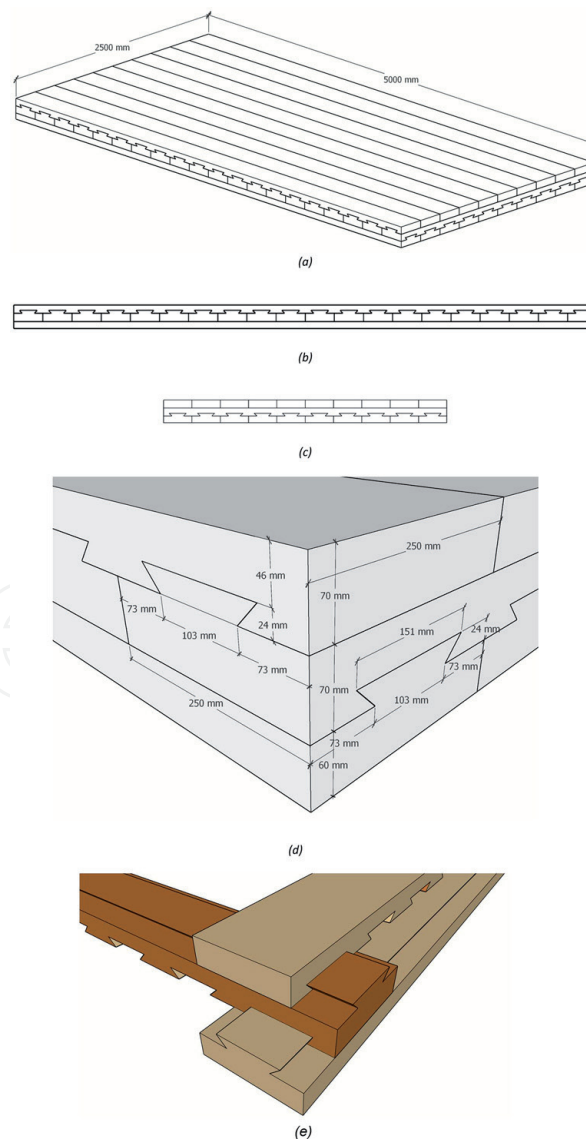


Figure 6. *Dovetail wood elements as floor slab alternative-1 (solid type): (a) isometric view; (b) front view; (c) side view; (d) with representative dimensions; (e) detail.*

unit can work on the same file, and the result is the same as desired. The number of layers can be varied, and the width and thickness of the wood can also vary according to need, and the hardness of the board is completely formed without adhesives, nails, staples, or other materials, with no size limitation unlike traditional EWPs such as CLT and LVL.

According to current construction practices of conventional EWPs and critical discussions with various industry professionals as the first step in design, geometrically original and technically sound 2D and 3D horizontal (e.g., floor slab) frame models are presented below.

For comparison with the CLT of equivalent dimensions, the optimal test size of the dovetail wood board will usually be taken as about 200 mm thick (three-layer),

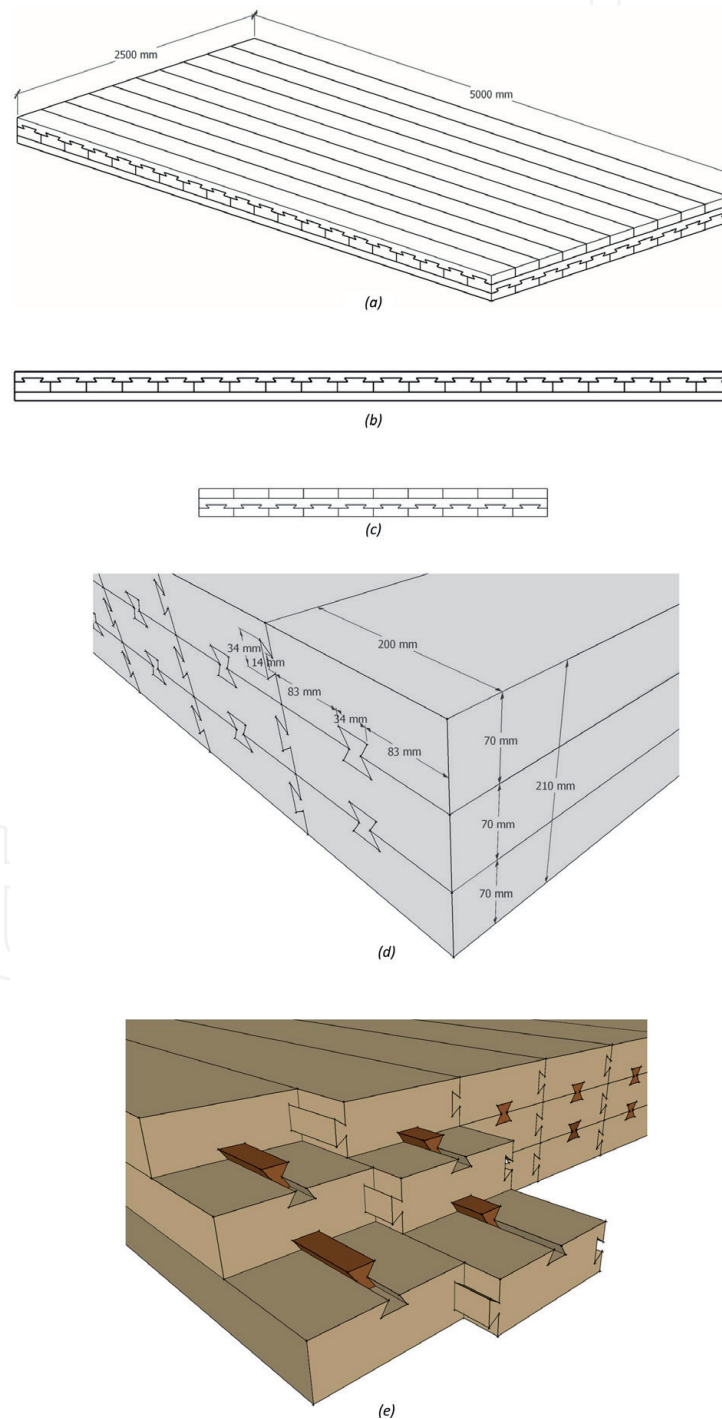


Figure 7. Dovetail wood elements as floor slab alternative-2 (key type): (a) isometric view; (b) front view; (c) side view; (d) with representative dimensions; (e) detail.

2500 mm wide, and 5000 mm long. Additionally, in the light of the abovementioned practical knowledge and discussions, the design, which was initially considered as five-layer, has been revised to three-layer to minimize the amount of waste products. Moreover, considering structural tests and other performance tests such as fire safety and sound insulation, it is predicted that the dimensions of building components may change, especially after structural analysis.

As can be seen in **Figure 6**, the “solid type” can be used as dovetail wood elements as an alternative to the floor slab, inspired by conventional dovetail connection, one of the oldest joining methods used in ancient temples and churches.

Figure 7 highlights “key type” with a similar structural mechanism with key laminated timber beams. However, since in the current literature, there are few studies (e.g., [55, 56]) on key-laminated beams that show similarities to our key type proposal in **Figure 6**, advantages and disadvantages of our key type can be

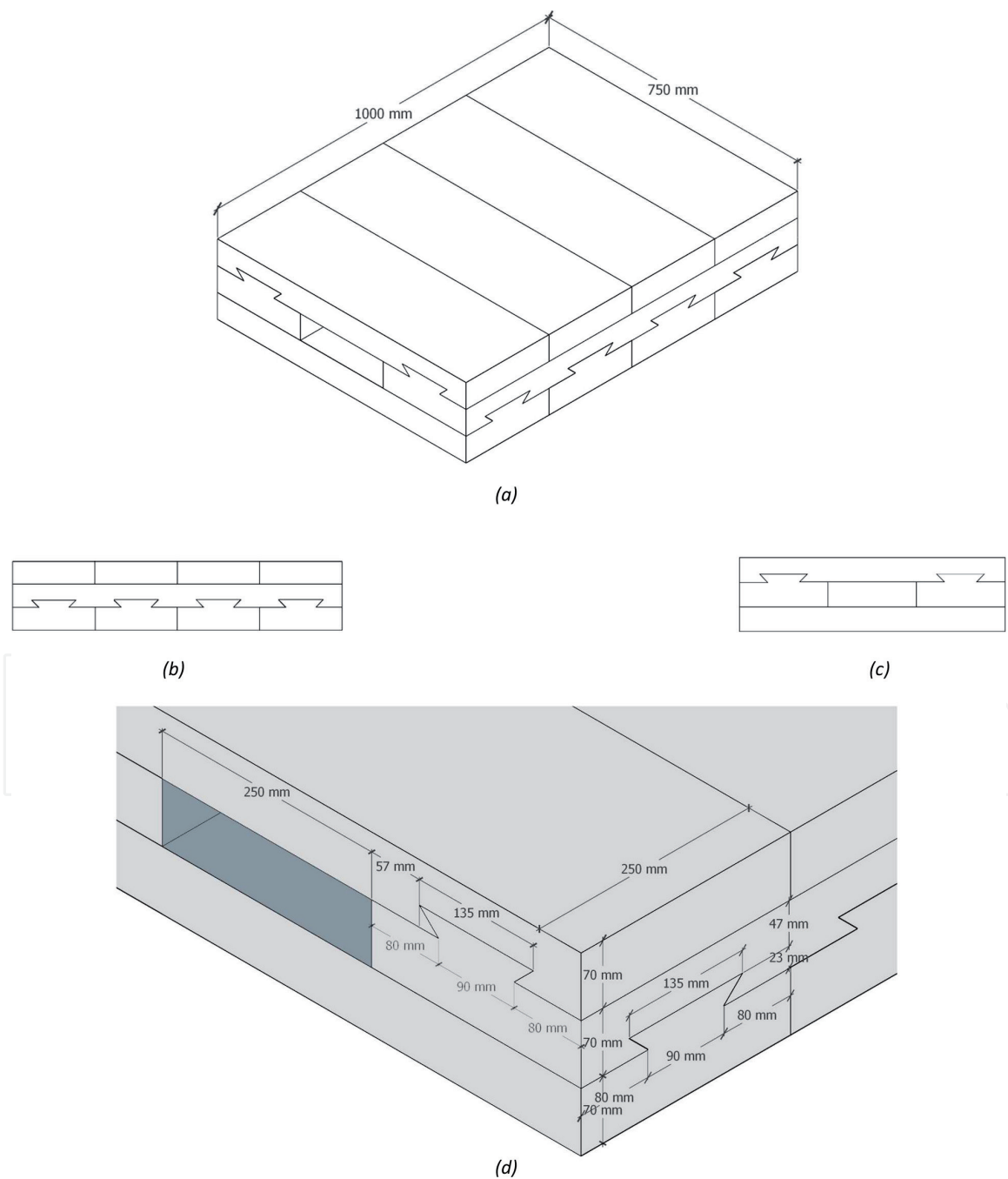


Figure 8. Dovetail wood elements as floor slab alternative-3 (hollow type): (a) isometric view with dimensions; (b) front view; (c) side view; (d) with representative dimensions.

revealed as a result of structural analyses and subsequent technical performance tests in the laboratory.

As shown in **Figures 8** and **9**, hollow type is a viable alternative due to its many advantages including reducing the dead load, improving the weight-to-strength ratio, ease of plumbing or electrical work, thus saving construction cost as in the cases of hollow concrete slab [57, 58] and hollow-core cross-laminated timber [59, 60].

After the geometric configuration design phase, structural analyses will be made, and it is planned to proceed to the prototype manufacturing phase. In this phase, softwood from gymnosperm trees such as pines and spruces will be used, taking into consideration its advantages such as workability, sustainability, and cost.

Here, first, the solid type shown in **Figure 6** will be manufactured and technical performance tests will be carried out compared with equivalent CLT elements as mentioned above. In this sense, as a result of the first technical evaluations made

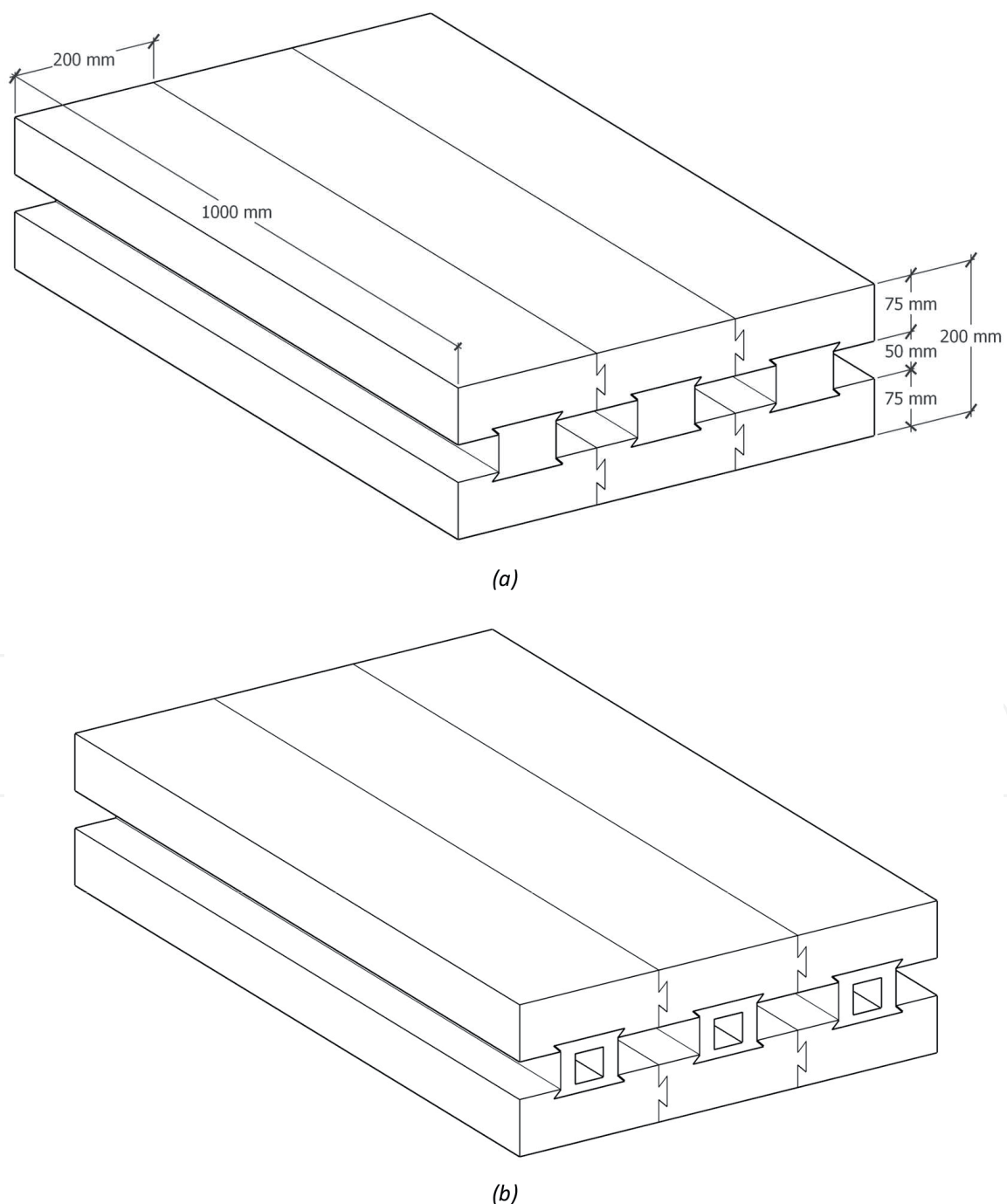


Figure 9.
Dovetail wood elements as floor slab alternatives-4 (hollow type-2).

with wood construction experts and structural designers, it is predicted that the structural performance tests, which represent the most critical phase of the comparison study to be conducted, will yield positive results considering DWBE's solid structure and joint details as seen in **Figure 6**. On the other hand, considering the future performance tests to be carried out as mentioned above, it is anticipated that as shown in **Figures 8 and 9**, hollow types' weight-strength advantage will make a great contribution to their structural performance, and the porous structure will make a big difference in their sound insulation performance.

4. Conclusion

Since there are no patented adhesive and nonmetallic dovetail wood panel solutions in the timber market [40], it has not been possible to carry out a comprehensive discussion on the similarities and differences of our proposals with other solutions. This study aimed to present various geometric configurations for dovetail wooden horizontal structural members in multistory building construction as ecologically sound engineering solutions through architectural modeling programs as the first step to developing DWBEs. The results are at the architectural design stage based on a theoretical approach taking into account current construction practices, but developed products will be finalized through market research after the technical performance tests (e.g., structural, fire, sound insulation, and airtightness tests) and necessary optimization processes. Therefore, currently, though DWBEs uptake for commercial applications is very limited, due to new studies such as DoMWoB project (*Dovetailed Massive Wood Board Elements for Multi-Story Buildings—see Acknowledgments*), the potential of the “innovative dovetail concept” will be further used in high-rise construction.

Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement No [101024593].

Funding

This project has also received funding (60 000 EUR) from the Marjatta and Eino Kolli Foundation for funding the technical performance tests including fire safety, structural, moisture transfer resistance and air-tightness, and sound insulation.

Thanks

The authors thank Dr. Ozlem Nur Aslantamer (Atılım University) for her great contribution to both initial design ideas and drawings.

IntechOpen

IntechOpen

Author details

Hüseyin Emre Ilgin*, Markku Karjalainen and Olli-Paavo Koponen
Tampere University, Tampere, Finland

*Address all correspondence to: emre.ilgin@tuni.fi

IntechOpen

© 2022 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/3.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. 

References

- [1] Alsheyab MAT. Recycling of construction and demolition waste and its impact on climate change and sustainable development. *International journal of Environmental Science and Technology*. 2021. DOI: 10.1007/s13762-021-03217-1. <https://link.springer.com/article/10.1007/s13762-021-03217-1#citeas>
- [2] Li D, Huang G, Zhu S, Chen L, Wang J. How to peak carbon emissions of provincial construction industry? Scenario analysis of Jiangsu Province. In: *Renewable and Sustainable Energy Reviews*. Leicestershire, UK: Loughborough University; Vol. 44. 2021. DOI: 10.1016/j.rser.2021.110953
- [3] IPCC. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge and New York: Cambridge University Press; 2013
- [4] UN Environment programme, building sector emissions hit record high, but low-carbon pandemic recovery can help transform sector—UN report. Available from: <https://www.unep.org/news-and-stories/press-release/building-sector-emissions-hit-record-high-low-carbon-pandemic> [Accessed: November 20, 2021]
- [5] Architecture 2030. *Why the Building Sector?* Available from: <https://architecture2030.org/why-the-building-sector/> [Accessed: November 20, 2021]
- [6] Bosman R, Rotmans J. Transition governance towards a bioeconomy: A comparison of Finland and The Netherlands. *Sustainability*. 2016;**8**(10): 1017. DOI: 10.3390/su8101017
- [7] Wood Building Programme. Finnish Ministry of Environment. Available from: [https://www.wym.fi/enUS/Land_use_and_building/Programmes_and_strategies/Wood_Building_Program/Wood_Building_Programme\(47800\)](https://www.wym.fi/enUS/Land_use_and_building/Programmes_and_strategies/Wood_Building_Program/Wood_Building_Programme(47800)) [Accessed: November 20, 2021]
- [8] Harte AM. Mass timber—the emergence of a modern construction material. *Journal of Structural Integration Maintenance*. 2017;**2**(3):121-132
- [9] Shahnewaz M, Tannert T, Alam MS, Popovski M. In-plane stiffness of cross-laminated timber panels with openings. *Structural Engineering International*. 2017;**27**:217-223
- [10] Stepinac M, Šušteršič I, Gavric I, Rajcic V. Seismic design of timber buildings: Highlighted challenges and future trends. *Applied Sciences*. 2020;**10**:1380
- [11] Ramage MH, Burrige H, Busse-Wicher M, Fereday G, Reynolds T, Shah DU, et al. The wood from the trees: The use of timber in construction. *Renewable and Sustainable Energy Reviews*. 2017;**68**:333-359
- [12] Carbon 12. Available from: <https://www.carbon12pdx.com/about> [Accessed: November 20, 2021]
- [13] Abrahamsen RB. *Mjøstårnet—Construction of an 81 m Tall Timber Building*. Garmisch-Partenkirchen, Germany: Internationales Holzbau-Forum IHF; 2017
- [14] Gambero J, Bocquet JF, Weinand Y. A calculation method for interconnected timber elements using wood-wood connections. *Buildings*. 2020;**10**(3):61. DOI: 10.3390/buildings10030061
- [15] Frihart CR. Introduction to special issue, wood adhesives: Past, present, and future. *Forest Products Journal*. 2015;**65**:4-8
- [16] Solta P, Konnerth J, Gindl-Altmutterb W, Kantnerc W, Moser J,

- Mitterd R, et al. Technological performance of formaldehyde-free adhesive alternatives for particleboard industry. *International Journal of Adhesion and Adhesives*. 2019;**94**: 99-131
- [17] Nguyen MN, Leicester RH, Wang C-H, Foliente GC. Corrosion effects in the structural design of metal fasteners for timber construction. *Structure and Infrastructure Engineering*. 2013;**9**(3): 275-284. DOI: 10.1080/15732479.2010.546416
- [18] Robert H, Falk PE, Baker AJ. Fasteners for exposed wood structures. *Wood Design Focus*. 1993;**4**(3):14-17
- [19] Khoshnava SM, Rostami R, Zin RM, Štreimikienė D, Mardani A, Ismail M. The role of green building materials in reducing environmental and human health impacts. *International Journal of Environmental Research and Public Health*. 2020;**17**(7):2589
- [20] Kozicki M, Guzik K. Comparison of VOC emissions produced by different types of adhesives based on test chambers. *Materials*. 2021;**14**(8):1924. DOI: 10.3390/ma14081924
- [21] Chang WS, Nearchou N. Hot-pressed dowels in bonded-in rod timber connections. *Wood and Fiber Science*. 2015;**47**(2):199-208
- [22] Sotayo A, Bradley D, Bather M, Sareh P, Oudjene M, El-Houjeyri I, et al. Review of state of the art of dowel laminated timber members and densified wood materials as sustainable engineered wood products for construction and building applications. *Developments in the Built Environment*. 2020;**1**:1-11
- [23] Ilgin HE, Karjalainen M, Koponen O. Review of the Current State-of-the-Art of Dovetail Massive Wood Elements. London, UK: IntechOpen; 2021
- [24] Toivonen R, Lähtinen K. Sustainability—A Literature Review on Concealed Opportunities for Global Market Diffusion for the Crosslaminated Timber (CLT) in the Urbanizing Society. Curitiba, Brazil: BioProducts Business; 2019
- [25] Lu B, Lu W, Zhong M, Wu W, Zhou P. Experimental investigation and analytical model of cross-laminated timber wall with coupled U-shaped flexural plate connectors. *Construction and Building Materials*. 2021;**307**:124984. DOI: 10.1016/j.conbuildmat.2021.124984
- [26] Pečnik JG, Gavrić I, Sebera V, Kržan M, Kwiecień A, Zajac B, et al. Mechanical performance of timber connections made of thick flexible polyurethane adhesives. *Engineering Structures*. 2021;**247**:113125. DOI: 10.1016/j.engstruct.2021.113125
- [27] Lukacs I, Björnfot A, Tomasi R. Strength and stiffness of cross-laminated timber (CLT) shear walls: State-of-the-art of analytical approaches. *Engineering Structures*. 2019;**178**:136-147
- [28] Xing Z, Wang Y, Zhang J, Ma H. Comparative study on fire resistance and zero strength layer thickness of CLT floor under natural fire and standard fire. *Construction and Building Materials*. 2021;**302**:124368. DOI: 10.1016/j.conbuildmat.2021.124368
- [29] Ronquillo G, Hopkin D, Spearpoint M. Review of large-scale fire tests on cross-laminated timber. *Journal of Fire Sciences*. 2021;**39**(5):327-369. DOI: 10.1177/073490412111034460
- [30] Li M, Zhang S, Gong Tian Z, Ren H. Gluing techniques on bond performance and mechanical properties of cross-laminated timber (CLT) made from *Larix kaempferi*. *Polymers*. 2021;**13**:733
- [31] Jasieńko J, Nowak T, Karolak A. Historical carpentry joints. *Journal of Heritage Conservation*. 2014;**40**:58-82

- [32] Jeong GY, Park MJ, Park JS, Hwang KH. Predicting load-carrying capacity of dovetail connections using the stochastic finite element method. *Wood and Fiber Science*. 2012;**44**(4): 430-439
- [33] Robeller C, Weinand Y. Interlocking folded plate—integral mechanical attachment for structural wood panels. *International Journal of Space Structures*. 2015;**30**:111-112. DOI: 10.1260/0266-3511.30.2.111
- [34] Pozza L, Scotta R, Trutalli D, Pinna M, Polastri A, Bertoni P. Experimental and numerical analyses of new massive wooden shear-wall systems. *Buildings*. 2014;**4**:355-374
- [35] Pozza L, Scotta R, Trutalli D, Polastri A. Behaviour factor for innovative massive timber shear walls. *Bulletin of Earthquake Engineering*. 2015;**13**:3449-3469
- [36] Jeong GY, Song JK. Evaluation of structural properties of dovetail connections under tensile load using three methods of data analysis. *Journal of Materials in Civil Engineering*. 2017;**29**(10):6017011
- [37] Sha B, Wang H, Li A. The influence of the damage of mortise-tenon joint on the cyclic performance of the traditional Chinese timber frame. *Applied Sciences*. 2019;**9**(16):3429. DOI: 10.3390/app9163429
- [38] Xie Q, Zhang B, Zhang L, Guo L, Wu Y. Normal contact performance of mortise and tenon joint: Theoretical analysis and numerical simulation. *Journal of Wood Science*. 2021;**67**:31. DOI: 10.1186/s10086-021-01963-x
- [39] Mashrah WAH, Chen Z, Liu H, Amer MA. Mechanical behaviour of a novel steel dovetail joint subjected to axial compression loading. *Engineering Structures*. 2021;**245**:112852. DOI: 10.1016/j.engstruct.2021.112852
- [40] Ilgın HE, Karjalainen M. Preliminary design proposals for dovetail wood board elements in multi-story building construction. *Architecture*. 2021;**1**(1):56-68. DOI: 10.3390/architecture1010006
- [41] Murdock JN. Stream restoration. In: Jørgensen SE, Fath BD, editors. *Encyclopedia of Ecology*. Amsterdam: Elsevier, Academic Press; 2008. pp. 3390-3397. DOI: 10.1016/B978-008045405-4.00077-X
- [42] Mitsch WJ. *Ecological Engineering: A New Paradigm for Engineers and Ecologists*, National Academy of Engineering, Engineering Within Ecological Constraints. Washington, DC: The National Academies Press; 1996. DOI: 10.17226/4919
- [43] Schönborn A, Junge R. Redefining ecological engineering in the context of circular economy and sustainable development. *Circular Economy and Sustainability*. 2021;**1**:375-394. DOI: 10.1007/s43615-021-00023-2
- [44] Matlock MD, Morgan RA. *Ecological Engineering Design Restoring and Conserving Ecosystem Services*. Hoboken, NJ: Wiley; 2010
- [45] Fraser M. *Design Research in Architecture: An Overview*. London: Ashgate; 2013
- [46] Akšamija A. *Research Methods for the Architectural Profession*. New York, NY, USA: Routledge; 2021
- [47] Short CA. What is 'architectural design research'? *Building Research & Information*. 2008;**36**(2):195-199. DOI: 10.1080/09613210701811015
- [48] Vasilenko NA. *General System Principles of Architectural Systems Formation*. IOP Conference Series: Materials Science and Engineering. 2020;**753**:32047

- [49] Luck R. Design research, architectural research, architectural design research: An argument on disciplinarity and identity. *Design Studies*. 2019;**65**:152-166. DOI: 10.1016/j.destud.2019.11.001
- [50] Gao Y. Design research in architecture: An overview edited by Murray Fraser. *The Design Journal*. 2015;**18**(2):291-294. DOI: 10.2752/175630615X14212498964439
- [51] Eilouti B. Scenario-based design: New applications in metamorphic architecture. *Frontiers of Architectural Research*. 2018;**7**(4):530-543. DOI: 10.1016/j.foar.2018.07.003
- [52] Luck R. Participatory design in architectural practice: Changing practices in future making in uncertain times. *Design Studies*. 2018;**59**:139-157. DOI: 10.1016/j.destud.2018.10.003
- [53] Bhooshan S. Parametric design thinking: A case-study of practice-embedded architectural research. *Design Studies*. 2017;**52**:115-143. DOI: 10.1016/j.destud.2017.05.003
- [54] Fu F. *Design and Analysis of Tall and Complex Structures*. Oxford and Cambridge: Butterworth-Heinemann, Elsevier; 2018
- [55] Miller JF, Bulleit WM. Analysis of mechanically laminated timber beams using shear keys. *Journal of Structural Engineering* (New York, N.Y.). 2011;**137**(1):124-132. DOI: 10.1061/(ASCE)ST.1943-541X.0000273
- [56] Miller JF. *Design and analysis of mechanically laminated timber beams using shear keys [PhD dissertation]*. Michigan, United States: Civil Engineering, Michigan Technological University; 2009
- [57] Ahmed IM, Tsavdaridis KD. The evolution of composite flooring systems: Applications, testing, modelling and Eurocode design approaches. *Journal of Constructional Steel Research*. 2019; **155**:286-300. DOI: 10.1016/j.jcsr.2019.01.007
- [58] Al-Shaarbaf IA, Al-Azzawi AA, Abdulsattar R. A state of the art review on hollow core slabs. *ARN Journal of Engineering and Applied Sciences*. 2018;**13**:9
- [59] Huang H, Lin X, Zhang J, Wu Z, Wang C, Wang BJ. Performance of the hollow-core cross-laminated timber (HC-CLT) floor under human-induced vibration. *Structure*. 2021;**32**:1481-1491. DOI: 10.1016/j.istruc.2021.03.101
- [60] *The CLT Handbook. CLT Structures—Facts and Planning*. Stockholm, Sweden: Swedish Wood; 2019. Available from <https://www.svensktra.se/siteassets/5-publikationer/pdf/CLT-handbook-2019-eng-m-svensk-standard-2019.pdf> [Accessed: November 20, 2021]