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Preliminary Design Proposals for Dovetail Wood Board Elements in Multi-Story Building Construction

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Abstract: Adhesives and metal fasteners play important roles in the composition and connections of engineered wood products (EWPs) such as cross-laminated timber and glue-laminated timber in the building construction industry. However, due to their petroleum-based nature, adhesives can cause toxic gas emissions, while metal fasteners compromise the end-of-life disposal and reusability of EWPs. These issues adversely affect the sustainable material properties of EWPs. Numerous studies have been conducted in the literature on the technological, ecological, social, and economic aspects of EWPs in construction with different construction solutions, but no studies have been conducted to evaluate the technical performance of dovetail wood board elements (DWBE) in multi-story or tall building construction. This study focuses on adhesive- and metal fastener-free DWBE as sustainable material alternatives for ecologically sensitive engineering solutions. Various preliminary design proposals are presented for DWBE using architectural modeling programs as an environmentally friendly approach intended for use in the timber construction industry. The research findings are based on a theoretical approach that has not yet been practically tested but is proposed considering existing construction practices that need further investigation, including technical performance tests. It is believed that this paper will contribute to the promotion and diffusion of DWBE for more diverse and innovative architectural and structural applications, particularly in multi-story timber building construction, as one of the key tools in tackling climate change challenges.

Keywords: timber/wood; dovetail wood board elements; multi-story building; building construction; sustainability

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1. Introduction

Due to their many technical advantages such as uniform strength, stiffness, and dimensional stability and environmental features such as low carbon and high thermal insulation, EWPs are increasingly competitive, especially in multi-story, even tall, wooden buildings [1–6] as in the cases of the 85 m and 18-story Mjøstårnet (Brumunddal, 2019) [7,8] (Figure 1), the 84 m and 24-story HoHo (Austria, 2020) [9] (Figure 2), and the 49 m and 14-story Treet (Bergen, 2015) buildings [10].

Adhesives and metal fasteners, with the standardization of the construction industry, are often employed as a connection in EWPs for contemporary timber buildings replacing conventional wood-to-wood assemblies [11]. In this context, adhesive bonding is among the key factors, and adhesives play an important role in EWPs, especially by helping to protect the wood, enabling the structure to be strong and light, and preventing shrinkage and expansion caused by natural humidity [12–15]. However, the use of adhesives raises some concerns about sustainability, recyclability, further processing, and wider environmental impact due to toxic gas emissions (e.g., VOC emissions and formaldehyde) during their lifetime and when burning from their petroleum-based ingredients [16–20]. Additionally, despite ongoing advances in this research area, critical questions still remain about environmentally friendly bio-based adhesives [2,21,22]. Metal fasteners, as well as adhesives,

are of great importance to EWPs [23,24], but they harm the end-of-life disposal, reusability, and recyclability of EWPs [20,25,26].



Figure 1. Mjøstårnet (Norway, 2019) (Source: Wikipedia).



Figure 2. HoHo (Austria, 2020) (Source: Wikipedia).

In the literature, numerous studies have been conducted on the technological, ecological, social, and economic aspects of EWPs in the construction industry with different building solutions; however, no studies have attempted to evaluate the technical perfor-

mance of DWBE in multi-story or tall construction [27]. Moreover, there is very limited research on DWBE, and state-of-the-art technology has studied DWBE on a per-member basis only, or at most on a small-scale prototype level—no more than a connection detail—from a limited structural perspective and mostly in a theoretical framework [28].

This study focuses on dovetail wood board elements as sustainable material alternatives for ecological engineering solutions. Based on one of the oldest joining methods (Figure 3), these elements can offer an adhesive- and metal-fastener-free sustainable solution: solid and completely pure wood that provides as healthy indoor air as possible [28]. On the other hand, various potential difficulties and drawbacks (e.g., dimensional stability) can be encountered when using only dovetail elements, i.e., glueless boards. In this sense, a large decrease in the equilibrium moisture content compared to the equilibrium moisture content during the manufacture and assembly of the boards can lead to greater shrinkage of the wood and thus the appearance of airiness between the individual boards, which can lead to an undesirable reduction in wall stiffness. Another potential disadvantage of using DWBE can result from the greatly reduced strength of the wood in the radial and tangential directions in certain configurations. However, it is thought that these potential problems can be eliminated with the optimization and improvements to be made in the light of the results of the performance tests, e.g., structural performance, moisture transfer resistance, and airtightness.



(**a**) (**b**)

Figure 3. Dovetail joint as one of the oldest joining methods: (**a**) detail from a Romanian church; (**b**) detail from an Indian temple (Sources: Wikipedia).

The research aimed to create higher value-added circular economy opportunities to promote the competitiveness of large-scale industrial timber construction at the local level and to support European climate policy as part of bio-economy and sustainable development. To achieve this purpose, the plan to develop DWBE for multi-story buildings for the global market has been proposed as a replacement for conventional EWPs (e.g., CLT, Glulam) by enabling the confidence of its technical performance and suitability within the interdisciplinary collaborations among architecture, structure, and building physics. To bring this idea to life, as a first but important step towards realizing it, this research presents different initial design proposals for DWBE through architectural modeling programs as an eco-friendly approach in the timber construction industry.

It is believed that this study will contribute to the dissemination of DWBE for different and innovative architectural and structural applications, especially in multi-story timber building construction, as one of the key tools in tackling climate change challenges.

In this study, wood or timber refers to engineered timber 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), glue-laminated timber (Glulam—made by gluing together several graded timber laminations with their grain parallel to the longitudinal axis of the section), 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), Massiv-Holz-Mauer® (MHM—a timber wall construction material consisting of dried softwood joined with fluted aluminum nails that require neither glue nor chemical treatment). Furthermore, in this study, 'multi-story building' and 'tall building' are defined as a building with over two stories and eight stories, respectively.

In the literature, many studies have been carried out on the technological aspects of wood with different construction solutions based on the use of EWPs products such as CLT (e.g., [29–37]). There is an extremely limited number of research on DWBE, and the literature about 'DWBE' is based on inadequate structural analysis and model testing of several types of jointing details rather than even evaluating the performance of a structural component, e.g., a shear wall or a whole structure. This prevents us from understanding the potential to break new ground in multi-story building construction, particularly in terms of environmental impact and recyclability, and reduces the 'innovative dovetail concept' to the level of connection detail. For this reason, it can be clearly said that there is no research on the use of DWBE in buildings, and it is thought that this research will contribute to filling this gap, especially in terms of design.

The history of the dovetail technique goes back to before Christ. Some of the earliest known examples of this technique are ancient Egyptian furniture embedded in First Dynasty mummies, stone pillars from Temples in India, as well as in Chinese ancient architecture [38,39]. In Europe, the dovetail joint is also called a swallowtail joint, a culvertail joint, or a fantail joint. Early residential constructions with timber-framed structures, dating from the 13th century, consisted of mortise and tenon joints, strengthened with wedges, notched joints with tenons, and dovetail joints [40]. Moreover, based on the familiarity of skilled woodworkers with design and manufacture, carpentry-type wood-wood joints were broadly utilized in the construction industry until the mid-20th century [41]. Although the various dovetail designs in Europe and Asia were generally ruled by practical considerations [42], inefficiencies resulting from overly conventional designs as well as high labor costs made these connections uncompetitive. Today, advances in CNC woodworking technology have re-established the cost-efficiency of carpentry-type wood-to-wood joints [28].

Among the most important studies on wood-to-wood connections such as dovetail wood joints in the last decade, Xie et al. [43] investigated the contact characteristics of mortise and tenon joints in the traditional timber structures by using structural modeling software including ABAQUS through UINTER interface. The simulation results were confirmed by the experimental results. The results showed that the user-defined normal elasto-plastic contact finite element model was more in line with the actual force state and mechanical behavior of mortise and tenon joints.

Gamerro et al. [11] presented a new concept of building components through tenon joints based on the idea of portable flat packs delivered directly and assembled on-site. They aimed to develop a computational model suitable for application to predict the semi-rigid behavior of joints and the effective bending stiffness of such structural elements. The results indicated the proposed calculation model was a practical methodology to obtain the stress distribution and the global displacements of interconnected elements using through tenon joints. Nevertheless, complementary studies should be carried out for the design of these elements, considering the building codes and construction market conditions.

Sha et al. [44] attempted to determine the effect of the damage of mortise-tenon joints on the cyclic performance of a traditional Chinese timber frame using the finite element method, in which the model was subjected to lateral cyclic loading and validated based on the results of an experiment. Three types of damage were proposed and idealized, including the gap between the mortise and tenon and damage at the top and the end of the tenon. The results indicated that the proposed damages to the joints have negative effects on the lateral behavior of the timber frame. Both the rigidity and energy dissipation capacity of the wooden frame is weakened by these damages.

Jeong and Song [45] evaluated the structural properties of dovetail connections under tensile load using three methods of data analysis. In the research, initial stiffness, yield load, yield displacement, and the ductility ratio values were determined according to the three different methods. The results underlined that the slope of the initial load-displacement curve is greatly affected by the gap of the dovetail joint, and the yield load and yield displacement values of dovetail connections are highly subject to the initial slope depending on the method used.

Branco and Descamps [46] presented several carpentry joints (e.g., tenon, notched, lap, and scarf joints) with some calculation rules and possible reinforcement techniques. The results are mainly highlighted as follows: (1) if the decay of wooden components is too great, then obviously the only solution is replacement; (2) if repair is necessary, certain reliable in situ assessment techniques are used to determine the level of intervention required; (3) there is still a noticeable lack of scientific results and design guidelines for retrofitting old carpentry joints, which obviously demonstrates the lack of research in this area; (4) to achieve competence, engineers need specialized tools for the design of doweled connections.

Jeong et al. [47] investigated the effects of geometric variables on the mechanical behavior of the dovetail connection and estimated its allowable load carrying the capacity through the finite element method with different stress distributions associated with geometric parameters. Results showed that shear and tension perpendicular to the grain stresses were found to be the most critical stresses. In addition, the strength of the dovetail connection estimated from the structural models was validated from the results of the experimental tests.

Ozkaya et al. [48] aimed to determine the effect of the number of joints in frames produced from Oriented Strand Board and the type of adhesive on the diagonal tensile strength of the frame using 152 samples from OSB following EN 2470 and ASTM-D 1037 test standards. The results showed that adhesive should be used in the corner joining of the dovetail joints.

Besides the studies mentioned above, other similar research [40,42,49–57] focused more on the structural analysis and model testing of various connection details in different geometric configurations, rather than evaluating the performance of a structural component, a floor slab, or the entire structure.

2. Research Methods

The study was carried out through an extensive literature search given in the previous section, mostly including peer-reviewed articles, conference proceedings, and similar research projects. Furthermore, in this study, architectural modeling was employed as a research method that is commonly used in architectural research [58–61]. Features of using the main business applications used in modern architectural design practice, complex object modeling methods (e.g., AutoCAD, SketchUp, and Revit), parametric modeling, and information modeling methodology of buildings are taken into account in the studies [62,63].

3. Findings

The innovativeness of DWBE is based on a new way of combining the understanding of the characteristics of wood and its potential, traditional woodworking skills, the mechanical ability to mill efficiently and exactly large wood boards, digital machining control, and digital design. Thus, the architect, structural engineer, and production unit manufacturing the board can work on the same file, and the result is the same as desired. The number of layers can be wide ranging, and the wood's width and thickness can be also varied according to the needs and the rigidity of the board is completely created without adhesive, nails, tap-punches, or other materials without size limits, unlike competition for CLT and LVL.

Based on existing construction practices of other EWPs such as the CLT as a first step in design and implementation, geometrically original and architecturally sound 2D and 3D horizontal (e.g., floor slab) and vertical (e.g., shear wall) frame models elements are presented below. For comparison with the CLT of equivalent dimensions, the optimal test size of the dovetail wood board will be mostly taken as follows: 200 mm thick (5-layer), 2500 mm wide, and 5000 mm long. On the other hand, the dimensions of the structural components may vary, especially in light of structural analysis followed by structural tests and other performance tests such as fire safety and sound insulation tests.

3.1. Preliminarily Design Proposals for the Horizontal Frame (Floor Slab)

As shown in Figure 4, the "solid/massive-type" can be used as dovetail wood board elements as an alternative to slab flooring. This was inspired by the dovetail [28], one of the oldest joining methods used in ancient temples and churches, shown in Figure 3.

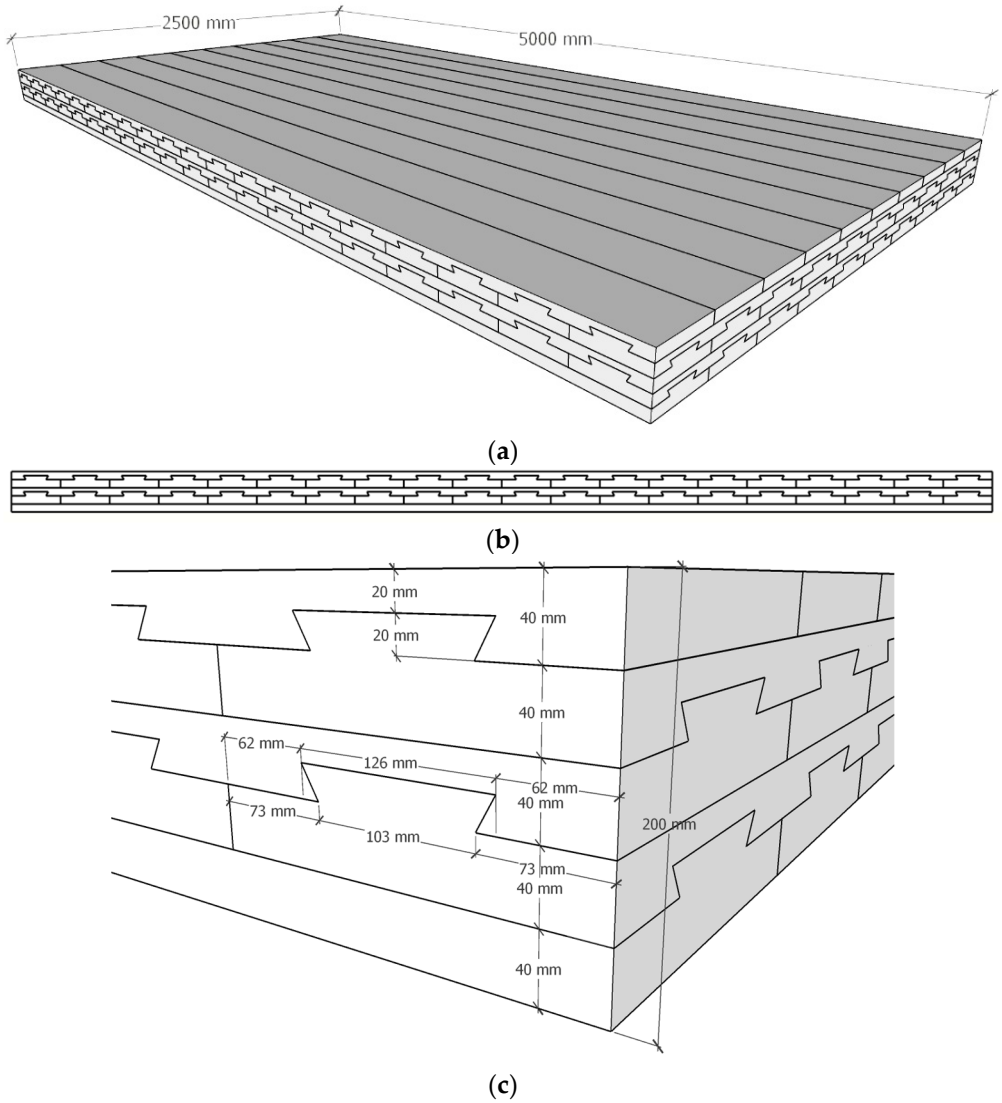


Figure 4. Dovetail wood board elements as floor slab alternative 1 (solid/massive-type): (**a**) isometric view, (**b**) side view, (**c**) with representative dimensions.

The "key-type" (Figure 5) can also be used, which has similar structural working principles with key-laminated wood beams [64].

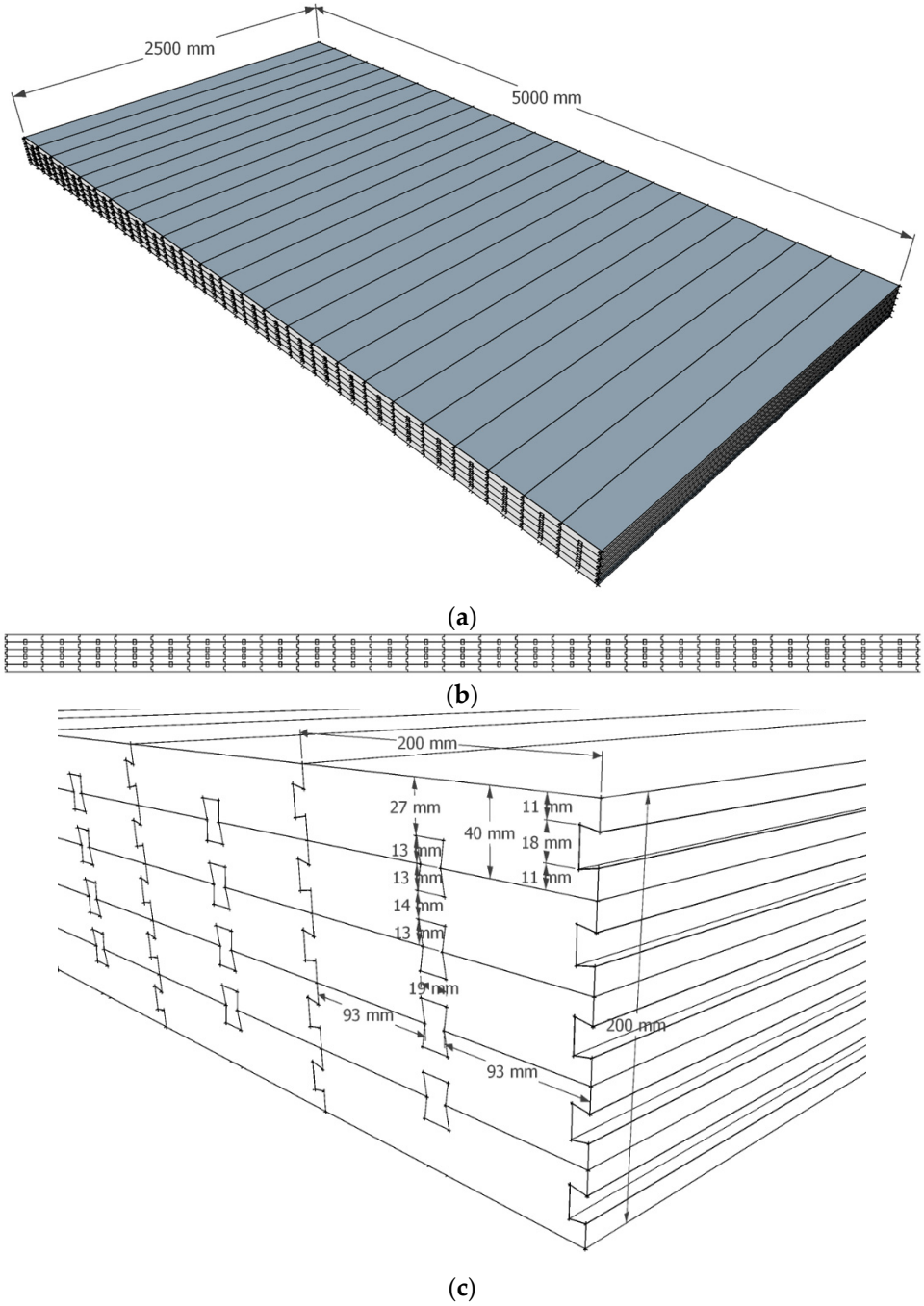


Figure 5. Dovetail wood board elements as floor slab alternative 2 (key-type): (**a**) isometric view, (**b**) side view, (**c**) with representative dimensions.

As shown in Figures 6 and 7, the hollow-type can also be a good alternative because of its many advantages such as reducing the hollow load, improving the weight–strength ratio, low heat and sound transmission properties, ease of installing plumbing or electrical works, and thus savings in construction costs as in the cases of hollow concrete slab [65–68] and hollow-core cross-laminated timber [69–72].

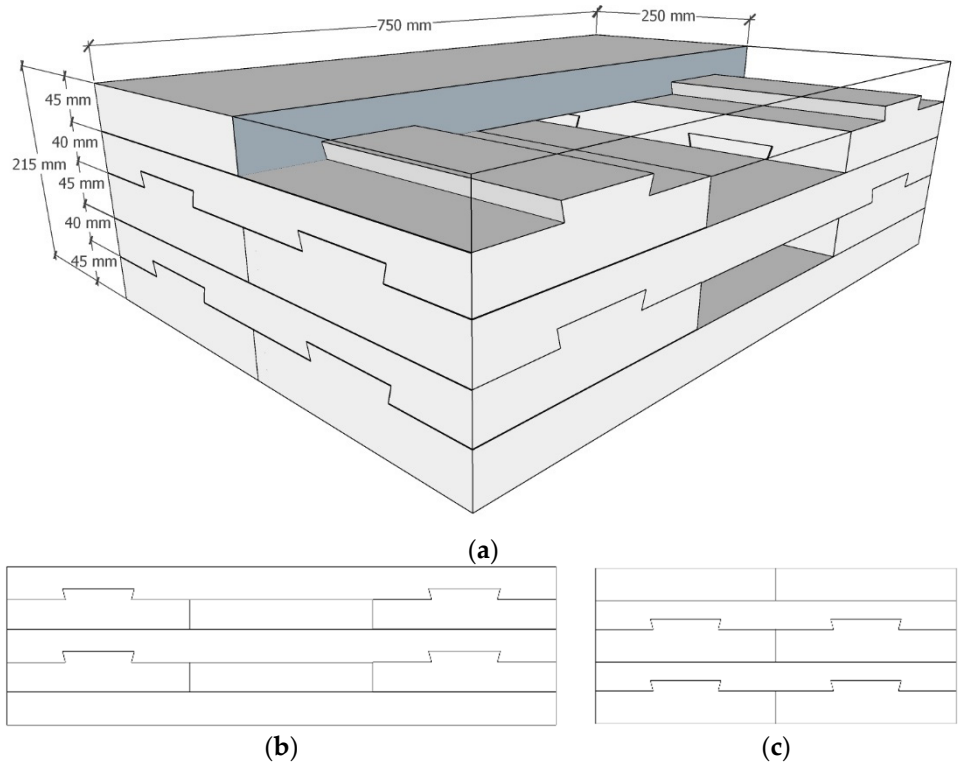


Figure 6. Dovetail wood board elements as floor slab alternative 3 (hollow-type-1): (**a**) isometric view with dimensions, (**b**) front view, (**c**) side view.

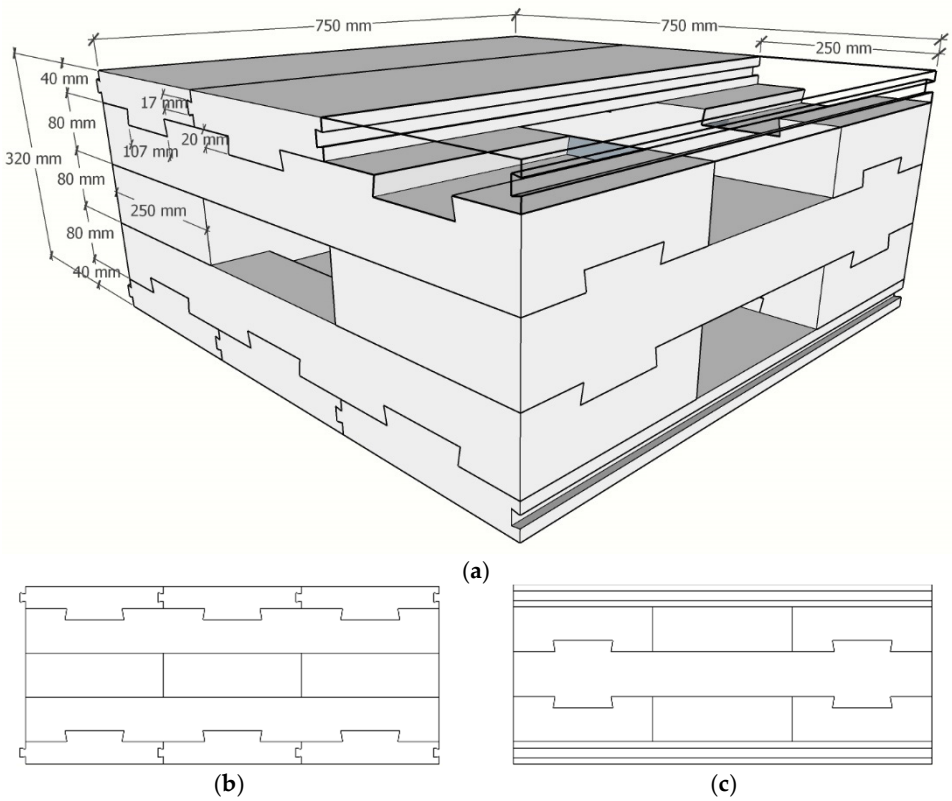


Figure 7. Dovetail wood board elements as floor slab alternative 4 (hollow-type-2): (**a**) isometric view with dimensions, (**b**) front view, (**c**) side view.

3.2. Preliminary Design Proposals for the Vertical Frame (Shear Wall)

The alternative types of shear wall, shown in Figures 8 and 9, which have similar advantages as with reinforced concrete hollow shear walls [73–75] (hence also on floor slabs as mentioned above), can be utilized as shear walls from dovetail wood board elements.

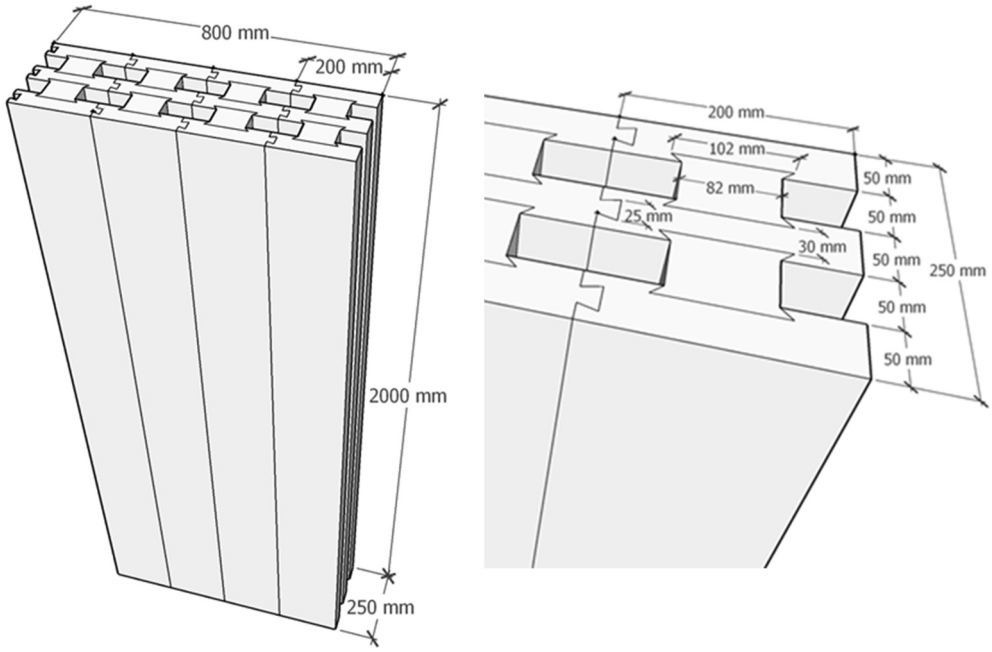


Figure 8. Dovetail wood board elements as shear wall alternative 1 (hollow-type 1) (isometric views with dimensions).

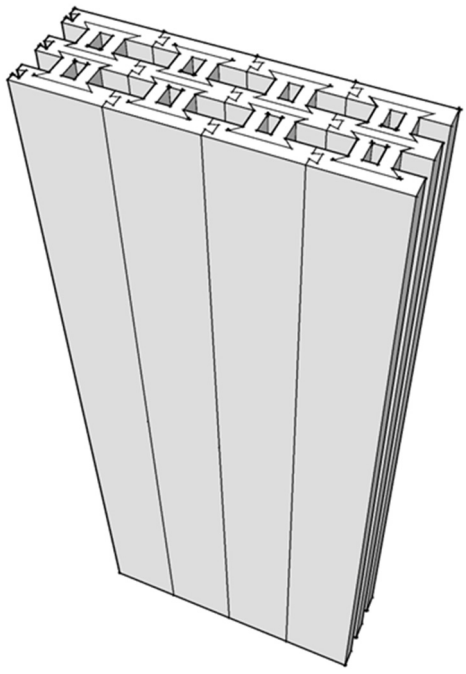


Figure 9. Dovetail wood board elements as shear wall alternative 2 (hollow-type 2).

4. Discussion and Conclusions

There are several non-adhesive and non-metallic wood panel solutions on the timber market (e.g., [76]), but there is no dovetail-based element for these solutions. Thus, it has not been possible to conduct a thorough discussion about the similarities and differences,

nor the pros and cons of our proposals as compared with other works. This study aimed to present several preliminary design proposals for dovetail wood board elements as ecologically sensitive engineering solutions through architectural modeling programs as a first step to develop DWBE in the global market in place of conventional EWPs. The findings of this study are based on a theoretical approach that has not yet been tested practically but is proposed considering current construction practices. However, after the technical performance (e.g., structural, fire, and sound insulation considerations; moisture transfer resistance; and airtightness) of the developed products is tested and the necessary optimizations are made, the products can be finalized with market research.

Currently, although DWBE uptake for commercial and structural applications is very limited, due to new research, e.g., The DoMWoB project (Dovetailed Massive Wood Board Elements for Multi-Story Buildings—see Acknowledgments), the potential of the 'innovative dovetail concept', inspired by one of the oldest joining techniques, could be further exploited in building construction, for example, in multi-story or even high-rise buildings.

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