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Chapter

Review of the Current State-of-the-Art of Dovetail Massive Wood Elements

Hüseyin Emre Ilgın, Markku Karjalainen and Olli-Paavo Koponen

Abstract

Engineered wood products (EWPs) have been progressively more being utilized in the construction industry as structural materials since the 1990s. In the content of EWPs, adhesives play an important role. However, because of their petroleum-based nature, adhesives contribute to toxic gas emissions such as formaldehyde and Volatile Organic Compounds, which are detrimental to the environment. Moreover, the frequent use of adhesives can cause other critical issues in terms of sustainability, recyclability, reusability, and further machining. In addition to this, metal connectors employed in EWPs harm their end-of-life disposal, reusability, and additional processing. This chapter is concentrating on dovetail massive wood elements (DMWE) as adhesive- and metal connector-free sustainable alternatives to commonly used EWPs e.g., CLT, LVL, MHM, Glulam. The dovetail technique has been a method of joinery mostly used in wood carpentry, including furniture, cabinets, log buildings, and traditional timber-framed buildings throughout its rich history. It is believed that this chapter will contribute to the uptake of DMWE for more diverse and innovative structural applications, thus the reduction in carbon footprint by increasing the awareness and uses of DMWE in construction.

Keywords: Dovetail joint technique, dovetail massive wood elements, engineered wood products, building construction, sustainability

1. Introduction

Wood is an indisputably renewable, ecological, and environmentally friendly material that has been widely used throughout history [1, 2]. One cubic meter of growing wood can bind about one ton of CO_2 from the atmosphere, the mass of wood is about 500 kg/m^3, and about half of this mass is carbon = 250 kg/m^3 [3, 4]. Forests are carbon sink and wood products are carbon storage. According to FAOSTAT, 488 million m^3 sawn wood were produced globally [5].

Moreover, thanks to its numerous positive impacts on the environment and potential cost-effectiveness compared to traditional materials such as reinforced concrete and steel, accompanied by its technological advances; wood, in the form of engineered wood products (EWPs), has come back to break into modern building utilization e.g., multi-story construction after more than a century [6–8].

In this industry, as a growing market in Europe, 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 soft wood joined with fluted aluminum nails that requires neither glue nor chemical treatment) have had an important position with the production capacity of more than 5 million cubic meter/year [9].

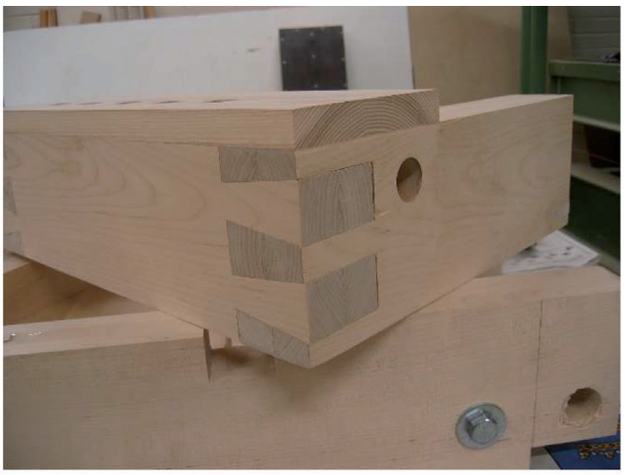
Particularly due to the easy coupling technique, airtightness, high rigidity, dimensional stability, and homogenous mechanical properties, EWPs e.g., CLT is competitive especially in multi-story wooden buildings [10, 11]. Similarly, Glulam external structural frame as a proven system for the buildings with over 10-story [12, 13] was used in the tallest wooden towers as in the cases of the 85 m and 18-story Mjøstårnet in Norway [14, 15], and 84 m and 24-story HoHo in Austria [16].

EWPs have been usually produced from the adhesive bonding of wood chips, flakes, veneer, or sawn wood sections, and/or the mechanical fastening of wooden sections to form larger sections, beams, panels, shear walls, or other structural members [17]. In these products, adhesives play an essential role particularly by helping save wood, making the structure light and strong, and restraining the contraction and expansion due to the inherent moisture. However, although there are advantages above associated with EWPs, the use of adhesives causes some concerns about their sustainability, recyclability, further machining, and broader environmental impact [9, 18].

More in particular, because of toxic gas emissions (e.g., formaldehyde and Volatile Organic Compounds) during their lifespan and while burning, resulting from their petroleum-based contents, the dominant use of adhesives has adverse effects on the environment e.g., climate change, air pollution, and human health [19–21]. Also, hardeners (e.g., amine and formaldehyde) in adhesives are irritating and skin sensitizing and are thus continually contact may cause allergic reactions [22]. Moreover, there are still critical questions about environmentally friendly biobased adhesives despite ongoing improvements in this research area [20, 23].

Besides several regulatory standards [24–26] addressing the points mentioned above, European Commission has a specific objective of improving air quality, which can also be achieved by reducing the use of harmful adhesives [27]. In addition to these detrimental substances, metal connectors used in EWPs have a negative impact on their end-of-life disposal, reusability, and recyclability [28]. It is worth noting here that the effect of moisture content on the mechanical and structural performance of DMWE should be particularly taken into account during design and construction phases because failure to control the moisture content of structural timber causes serious structural problems, such as excessive deflection of beams.

Therefore, this chapter is focusing on the dovetail joint technique and dovetail massive wood elements. Based on one of the oldest joining methods (see examples in **Figure 1**), these elements can offer a sustainable solution that is solid and completely pure wood enabling as healthy indoor air as possible (adhesive-&metal-connectors-free). It is believed that using the potential of DMWE will contribute to increase the competitiveness of large-scale industrial wooden construction and to create higher value-added circular economy opportunities as part of the bio-economy and sustainable development all over the world.



(a)



(b)



(c)

Figure 1.
Dovetail joints: (a) a finished dovetail joint, (b) dovetailed woodworking joints on a Romanian church, (c) stone pillar at the Vazhappally Maha Siva Temple (source: Wikipedia).

2. Historical background of dovetail joint technique

In history, the dovetail technique is a joinery method most used in woodwork (i.e. carpentry), including furniture, cabinets, log buildings, and traditional wood-framed structures. The history of the dovetail joint technique goes back to before Christ. Some of the earliest well-known examples of this technique were in ancient Egyptian furniture buried with mummies dating from the First Dynasty, stone pillars at the Temples in India (**Figure 2**) as well as Japanese and Korean traditional buildings [29, 30]. Besides these, this technique was utilized in Chinese ancient architecture [31, 32], where the dovetail joint was introduced - national building codes and construction methods in Song Dynasty in 1103 - as one of the primary joint methods employed in the oldest timber buildings in China [33]. Additionally, during the earliest times to the Middle Ages, in Egypt, the construction of cabinets was based on the mortise and tenon, dovetail, and mitred joints [34]. In Europe, the dovetail joint is also called a swallowtail joint, a culvertail joint, or a fantail joint [35].

The first residential constructions with wood-framed structures from the 13th century consisted of mortise and tenon joints, strengthened with wedges, notched joints with tenons, and dovetail joints [36]. Notable examples of connecting the roof rafter and beams involved making use of the dovetail joint (**Figure 3**) were

churches in the 14th century [36]. The roof structure of the Church of St. Jacob in Torun (16th century) was one of the oldest preserved examples, which includes notched joints with dovetail tenons [37]. Moreover, as Polish churches, the Church in Cewków (**Figure 4**) and the Church in Chotylub (**Figure 5**) were among remarkable examples of wood-framed buildings with dovetail wall-corner joists from the 19th century.

Based on the skilled woodworkers' familiarity with design and manufacture, carpentry-type wood-to-wood joints were widely used in building construction till

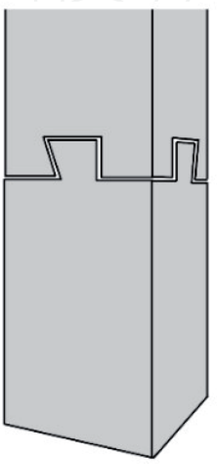


Figure 2.
A stone pillar at a temple in India (drawn by Emre ILGIN).

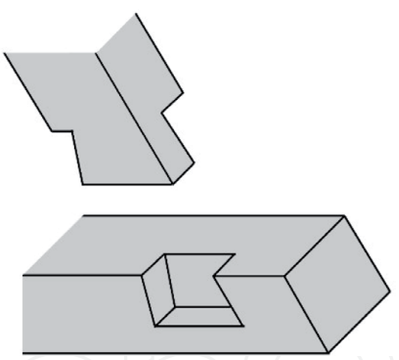


Figure 3.
Dovetail joint (drawn by Emre ILGIN).



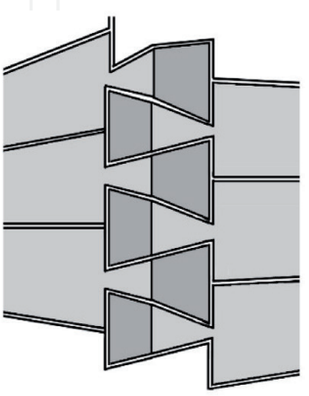


Figure 4.
The Church in Cewków, Poland (left) (source: Wikipedia) with dovetail corner detail (right) (drawn by Emre ILGIN).

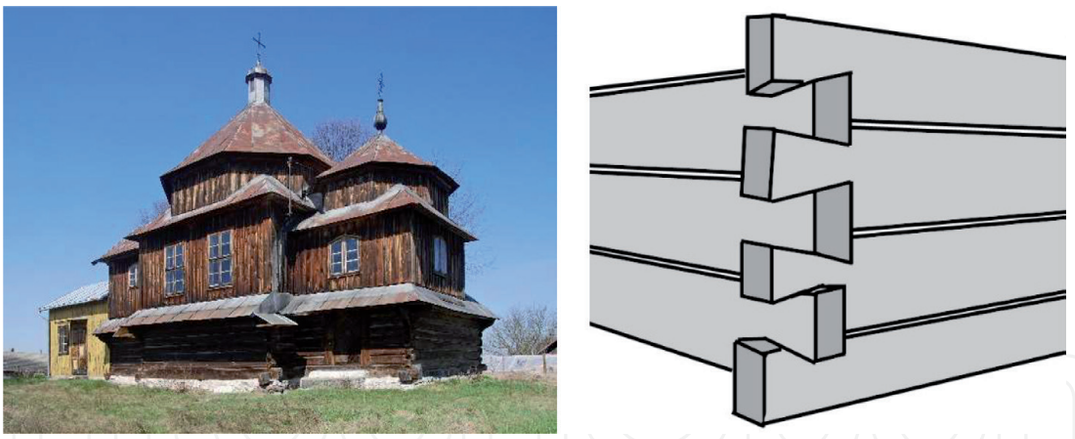


Figure 5.
The Church in Chotylub, Poland (left) (source: Wikipedia) with dovetail corner detail (right) (drawn by Emre ILGIN).

the mid-20th century [38]. Different dovetail designs in Europe and Asia often govern practical considerations [39]. However, high labor costs and inadequacies due to excessively traditional designs rendered these joints uncompetitive. Advancements in CNC wood processing machines re-established the cost-effectiveness for carpentry-type wood-to-wood joints.

3. The current state-of-the-art of dovetail massive wood elements

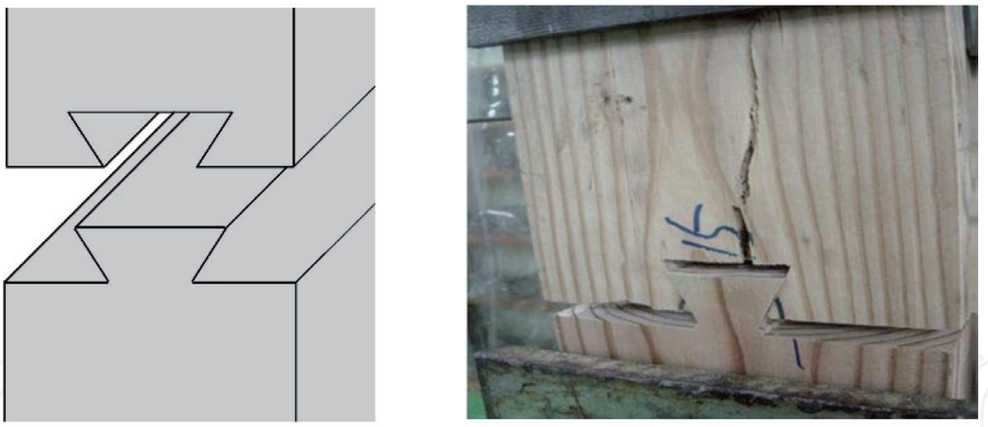
In the literature, thus far, there have been numerous studies regarding the technological aspects of timber in construction with different building solutions based on the utilization of engineered timber products such as CLT [40–43]. However, there is a limited number of researches (e.g., [44]) on dovetail massive wood elements (DMWE). To date, previous studies about DMWE is based on a few papers mostly about structural analysis and model testing of several types of joint details rather than even evaluating overall technical performance (e.g., structural, fire, sound) of a structural component such as a column, a beam, a shear wall or an entire structure.

Among these most prominent studies conducted in the last decade, Jeong et al. scrutinized the effects of geometric variables on the mechanical behavior of dovetail connection (**Figure 6**) through finite element method analysis together with experimental tests [45]. There different were parameters such as various tenon angles and tenon heights with three representative failure modes. The results showed that the geometry that maximizes the load-bearing capacity is the 57-degree tenon angle and the average allowable load for the dovetail joint is calculated as 21.4kN.

Also, failure modes of dovetail connection were dominated by tension perpendicular to the shear stress. Furthermore, planned failure criteria correlated with the critical stress played an important role in the projection of load-bearing capacity from dovetail connection.

Pang et al. studied the effects of size ratios on dovetail joints in Korean traditional timber building by examining moment resistance of various sizes of dovetail joints following experimental procedures together with dimensional analysis (**Figure 7**) [39]. It was observed that the average maximum and yield moment resistance was increased as the scale ratio was increased. As a result, moment resistance confirmed the similitude theory.

Tannert et al. presented various reinforcement methods (e.g., with self-tapping screws, with adhesive layer) to enhance the structural performance of rounded



(a) (b)

Figure 6.
(a) The dovetail joist for the test specimen (drawn by Emre ILGIN), (b) tension perpendicular to the grain failure at mortise in dovetail connection [45].

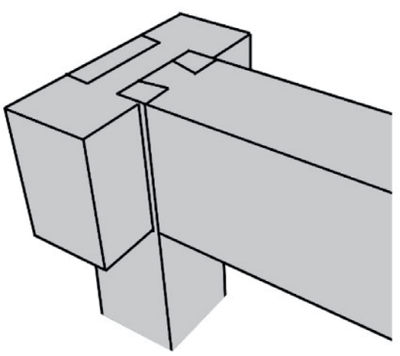


Figure 7.
The dovetail joist for the test specimen (drawn by Emre ILGIN).

dovetail joints (**Figure 8**) under static short-term shear loading [38]. Using the test series, comparisons between reinforced and non-reinforced joints were made to assess the potentials and limitations of different reinforcement methods. Based on the test results, adhesive-reinforced-rounded dovetail joints were proposed to improve structural performance under predefined loading conditions.

In the paper entitled 'Interlocking Folded Plate - Integral Mechanical Attachment for Structural Wood Panels', Robeller and Weinand built folded thin shell prototype consisting of timber panels by utilizing automatic fabrication of cabinetmaking joints, i.e. dovetail joints without adhesive (**Figure 9**) [46]. This interlocking arch prototype was constructed from 21 mm LVL panels and 12 mm

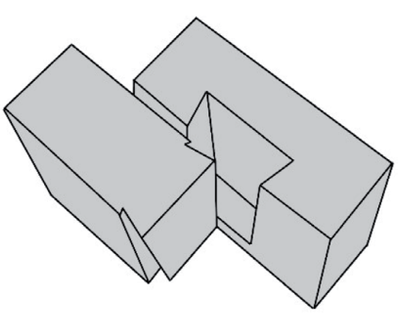


Figure 8.
The rounded dovetail joist for the test specimen (drawn by Emre ILGIN).

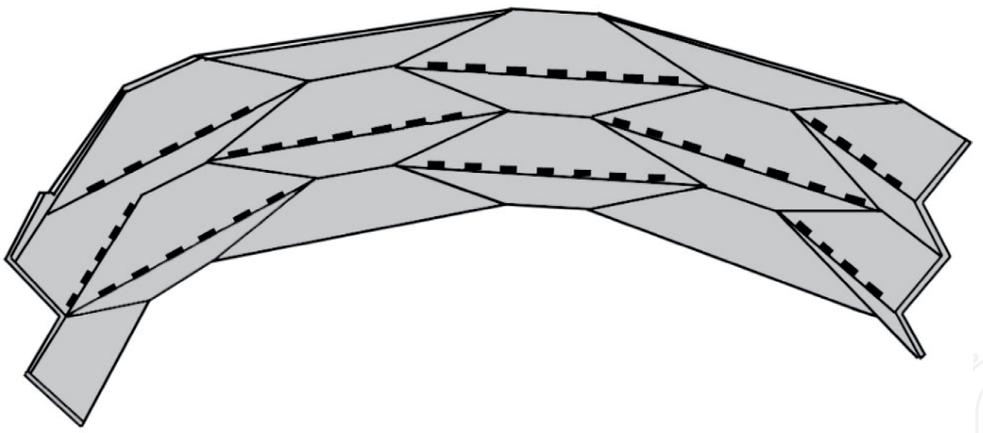


Figure 9.
Folded-plate arch prototype (drawn by Emre ILGIN).

plywood with a self-weight of 192 kg and a span of 3 meters to provide input on the load-carrying capacity of integrated joints. It was recommended that further research is needed for large-scale building applications.

Pozza et al. simulated and tested structural behaviors of three massive wooden shear wall configurations including the cross-laminated-glued wall, cross-laminated-stapled wall, and layered wall with dovetail inserts under seismic loads. According to the results, all configurations had good dispersion capacity and could be employed well for seismically vulnerable zones [47]. Similarly, Pozza et al. examined four massive wooden shear walls through experimental tests e.g., subjecting to compressive stress and numerical simulations. Analyzed shear wall configurations were CLT panels with glued interfaces together with massive timber panels adopting steel staples (stapled wall) or timber dovetail inserts to unite the layers (layered wall) [48]. Results indicated that all four variations offer a feasible construction technique for earthquake-prone zones.

Besides the abovementioned studies, other research showed that the critical aspects of the structure of material and failure behaviors without considering the effects of material properties and geometric configurations [49–51].

4. Types of dovetails

Throughout history, there are four most prevalent types of joints to be employed to fit walls together in building construction (**Figure 10**) [52, 53]:

i. double notch,

ii. half notch,

iii. "the lock", also called a "German" or "Saxon" joint (can be seen in different parts of the world e.g., the east of the Carpathian Mountains, northern Romania, Finland – *known as 'Hammasnurkka' or a 'toothed' corner joint*),

iv. full dovetail (fishtail) notch.

Joints were usually doweled, but round logs were often joined by undoweled 'saddle notched' joints. Although different types of joints were able to use in different parts of a wall, probably the most archaic type, the double notch was used

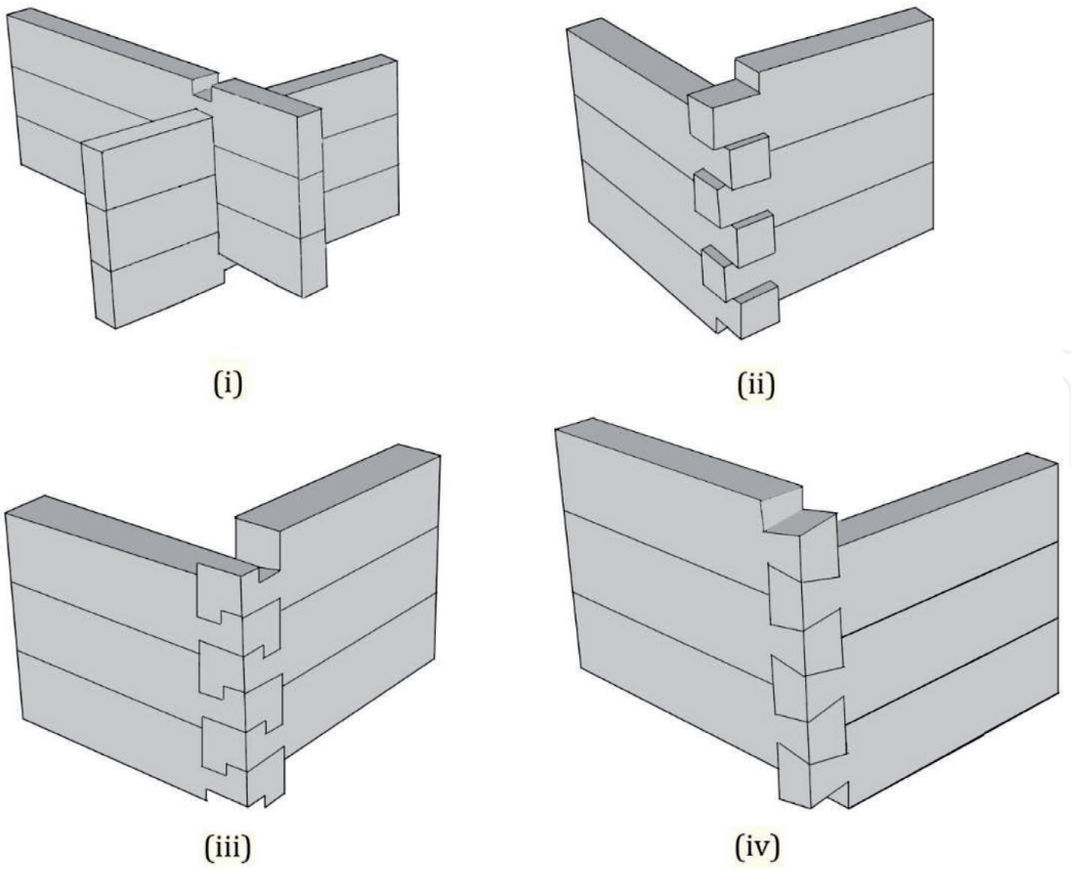


Figure 10.
Four types of carpentry joints: (i) double notch, (ii) half notch, (iii) the lock joint, (iv) full dovetail notch (drawn by Emre ILGIN).

directly under the deep eaves; the half notch was built over the eaves where the walls were to be planned or laid [53]. The full dovetail notch possibly began to be widely used in the 18th century.

Double notch is better than half notched joint as the beam is not weakened with respect to its load-bearing support, where skew angle and the notch depth are important parameters [54–56]. On the other hand, "the lock" is generally used for beams of large dimensions. As a rule, the four types of joints mentioned above can transfer both compressive and shear stresses, and dovetail connections can also transfer relatively small tensile stresses [57].

It is also worth mentioning here that in addition to the wood construction, throughout history, there are many different types of dovetail joint used in wooden furniture design, which can also be a source of inspiration for the construction industry of today, as follows (**Figure 11**) [34]:

(a) through dovetail, (b) lapped dovetail, (c) double lapped dovetail, (d) secret mitred dovetail. Joints used in carcases: (e) cross rails dovetailed into solid side, (f) cross rails dovetailed into framed side, (g) top dovetailed to side, (h) top dowelled to side, (i) top rebated, (j) housing, (k) tapered dovetail housing.

5. Conclusion

As one of our best allies in combating the climate crisis, timber is in the foreground due to its environmental-friendly features such as low carbon emissions in processing and carbon sequestration. In this sense, engineered wood products are increasingly used in the construction industry. However, adhesives used in their

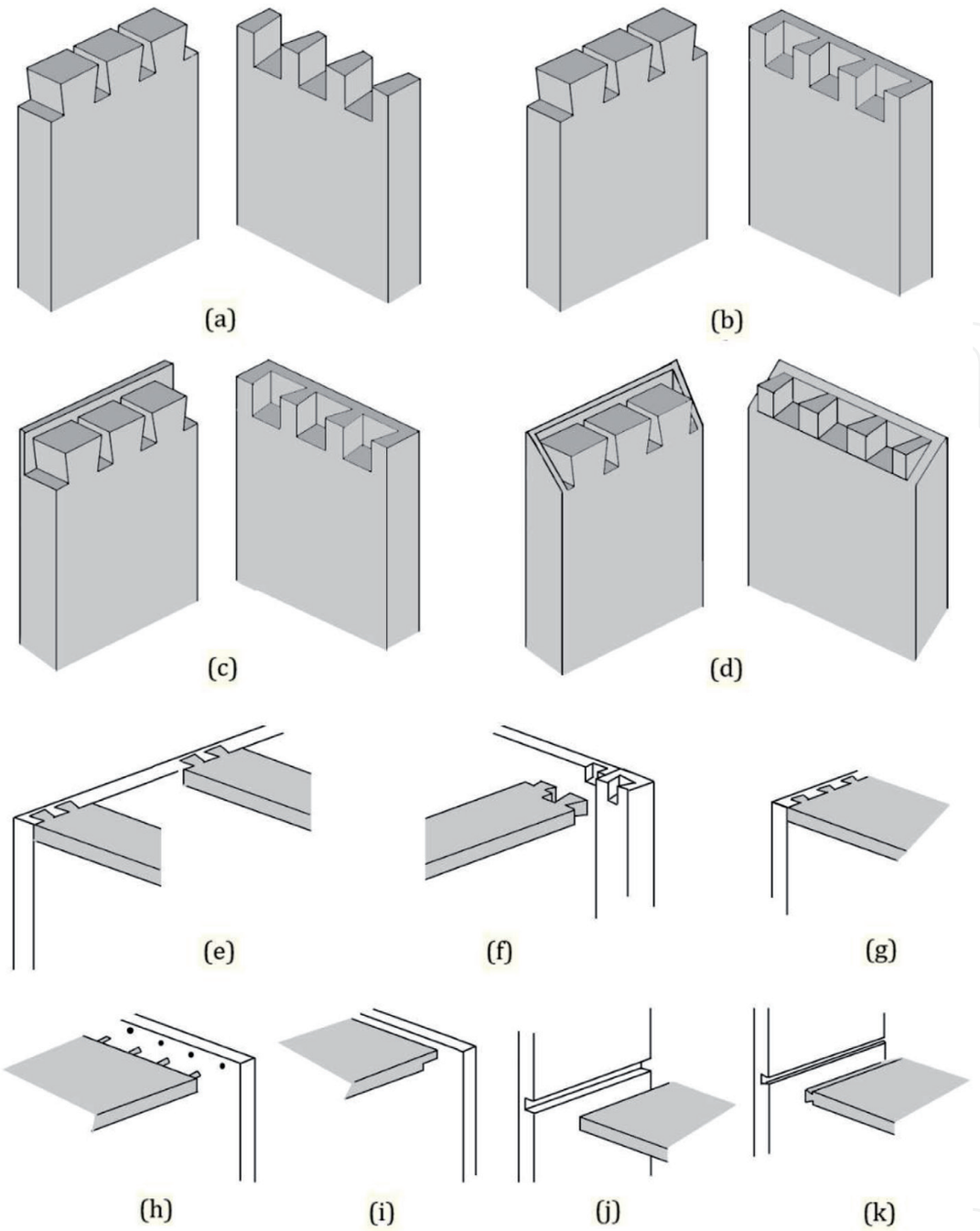


Figure 11.
Examples of dovetail joints in wooden furniture design: (a) through dovetail, (b) lapped dovetail, (c) double lapped dovetail, (d) secret mitred dovetail. Joints used in carcases: (e) cross rails dovetailed into solid side, (f) cross rails dovetailed into framed side, (g) top dovetailed to side, (h) top dowelled to side, (i) top rebated, (j) housing, (k) tapered dovetail housing (drawn by Emre ILGIN).

content contribute to toxic gas emissions, which are harmful to the environment and human health. Additionally, metal connectors utilized in EWPs threaten their end-of-life disposal and reusability. At this point, dovetail massive wood elements can be a sustainable alternative to commonly used EWPs due to their adhesive- and metal connector-free nature.

The history of the dovetail joint technique predates Christ. This technique has been widely used in many fields such as furniture design, cabinets, various traditional buildings e.g., churches in different parts of the world. To date, the state-of-the-art scrutinized DMWE only either at the member-based level or at most, small-scale-prototype level - not more than a connection detail - from a limited structural point of view and mostly in a theoretical framework. In other words,

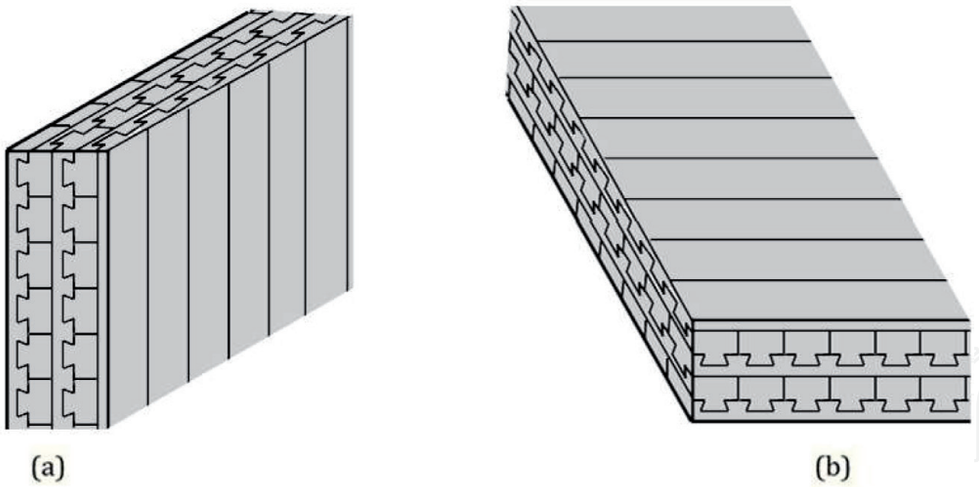


Figure 12.
Dovetail massive wood board elements: (a) vertical structural element, (b) horizontal structural element (drawn by Emre ILGIN).

literature about 'DMWE' 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.

Although at present, the intake of DMWE for commercial and structural applications is limited, thanks to new research e.g., DoMWoB project (Dovetailed Massive Wood Board Elements For Multi-Story Buildings) (see acknowledgments) (**Figure 12**), the potential of groundbreaking 'innovative dovetail concept' can be further exploited in building construction e.g., multi-story or even tall buildings.

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