DOVETAILED MASSIVE WOOD BOARD ELEMENTS FOR MULTI-STORY BUILDINGS

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ABSTRACT

Due to easy connection technique, airtightness, and high rigidity, engineered wood products (EWPs) e.g., Cross-laminated timber (CLT) can compete, especially in multi-story timber buildings. In EWPs, adhesives play an important role, particularly by helping to protect the wood, making the structure light and strong, and relieving expansion and contraction due to natural moisture. However, the use of adhesives raises some concerns about EWPs' sustainability, recyclability, and wider environmental impact. There is still room for a solution of solid and pure wood based on one of the oldest traditionally used joining methods, providing dovetailed massive wood board elements (DMWBE) that offer as healthy indoor air as possible without adhesives and metal binders. Numerous studies have been done in the literature on the technological, ecological, social, and economic aspects of EWPs in construction with different building solutions, but no attempt has been made to evaluate the technical performance of DMWBE in multi-story buildings. This research aims to create higher value-added circular economy opportunities to increase the competitiveness of Finnish large-scale industrial timber structures at the local level and to support European climate policy as part of bio-economy and sustainable development.

Key Words: Dovetail; Massive Wood; Wood Board Element; Wood Construction; Multi-Story Building.
INTRODUCTION

As a result of global urbanization, the trend to build more vertical cities, namely multi-story (2-story high or more) and tall buildings (over 8-story), has been becoming more suitable for changing lifestyles, economics, and urbanization (Hewitt and Graham, 2015; Harris, 2015; Ilgın, 2018; Ilgın et al., 2021a). Even Scandinavian cities could be now on the cusp of their high-rise revolution. Furthermore, building higher has been gradually gaining popularity as in the cases of many tall towers e.g., 180m Trigoni Tower 1, Finland; 237m Tellus Tower 1, Sweden; 320m Bestseller Tower, Denmark (CTBUH, 2021).

As a renewable material, wood is ecological and environmentally friendly: 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 (Tolppanen et al., 2013; Aaltonen, 2019). Forests are carbon sinks and wood products are carbon storage. Therefore, it is reasonable to use so much massive wood as possible particularly in multi-story construction (Ilgın and Karjalainen, 2021; Tulonen et al., 2021).

Moreover, due to its substantially lower carbon footprint and potential cost-effectiveness compared to traditional materials such as reinforced concrete and steel, and numerous positive impacts on the environment, accompanied by its technological advances; wood, in the form of EWPs, has come back to break into the multi-story building, and even tall building, utilization after more than a century (Kremer and Symmons, 2015; Toppinen et al., 2018a; Karjalainen et al., 2021). In multi-story wooden construction, Europe has been leading the way with many pioneering projects (CTBUH, 2021).

Before the early 1990s, most of the wooden buildings in European countries were limited to 1 or 2-story because of fire performance regulation restrictions (Xia et al., 2014); while in recent years, due to the national building regulations shifting from being prescriptive to functional or performance-based, multi-story wooden construction has been gaining acceptance in European countries (Östman and Källsner, 2011). Concordantly, a wide variety of EWPs is currently available on the market. They are gradually replacing conventional building materials for multi-story construction (Harte, 2017; Kuzman et al., 2018).

In this sense, the multi-story wooden buildings have been a new promising industry with a high capacity for supporting the bioeconomy and technologically refurbishing construction sector (Hurmekoski et al., 2018; Toppinen et al., 2018b; Karjalainen and Ilgın, 2021). They can contribute to social well-being both within primary production and within wood-based value-chains (Lähtinen et al., 2016). In this industry, as a growing market in Europe, EWPs e.g., CLT (cross-laminated timber, 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), LVL (laminated veneer lumber, made by bonding together thin vertical softwood veneers
with their grain parallel to the longitudinal axis of the section, under heat and pressure), MHM (Massiv-Holz-Mauer®, a timber wall construction material consisting of dried softwood joined with fluted aluminum nails that require neither glue nor chemical treatment) have had an important position with the production capacity of more than 5 million cubic meter/year (Guan et al., 2018).

Due to the easy coupling technique, airtightness, and high rigidity, EWPs e.g., CLT is competitive especially in multi-story wooden buildings (Karjalainen, 2017; Karjalainen, 2019). Similarly, Glulam external structural frame as a proven system for the buildings with over 10-story (Abrahamsen and Malo, 2014; Ramage et al., 2017) was used in the tallest wooden towers as in the cases of the 85m and 18-story Mjøstårnet in Norway (Figure 1), and 84m and 24-story HoHo in Austria (HoHo, 2021) (Figure 2).

Figure 1. Mjøstårnet (Norway, 2019)  Figure 2. HoHo (Austria, 2020)  (Source: Wikipedia)                            (Source: Wikipedia)

In EWPs, adhesives play an essential role particularly by helping save wood, making the structure light and robust, and moderating the expansion and contraction due to the inherent moisture. On the other hand, the use of adhesives causes some concerns about their sustainability, recyclability, and broader environmental impact (Chang and Nearchou, 2014; Guan et al., 2018).

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 (Hemmila, 2017; Adhikari and Ozarska, 2018). Furthermore, there
are still critical questions about environmentally friendly biobased adhesives despite continuing advancements in this research area (Norström et al., 2015; Hemmila, 2017).

Besides several regulatory standards (California Air Resources Board, 2009; WHO, 2010; BS EN 13986, 2015) addressing the points mentioned above, the European Commission (2011) has a specific objective of improving air quality, which can also be achieved by reducing the use of harmful adhesives. In addition to these detrimental substances, metal connectors used in EWPs harm their end-of-life disposal, reusability, and recyclability (Sotayo et al., 2020). Thus, there is still room for a solution that is solid and completely pure wood enabling as healthy indoor air as possible, adhesive-&metal-connectors-free DMWBE based on one of the oldest joining methods used traditionally.

In the literature, numerous studies have been conducted on the technological, ecological, social, and economic aspects of EWPs in the construction with different building solutions (Toivonen and Lähtinen, 2019) however, no studies have attempted to evaluate the technical performance of DMWBE in multi-story or tall construction (Ilgın et al., 2021b). Overall, this research aims to increase the competitiveness of Finnish large-scale industrial wooden construction at the local level and to create higher value-added circular economy opportunities in support of European climate policy as part of the bio-economy and sustainable development.

To achieve this goal, DMWBE for multi-story buildings to the global market as a replacement of conventional EWPs e.g., CLT, Glulam will be developed by enabling the confidence of its technical performance and suitability within the interdisciplinary collaborations among architecture, structure, and building physics in the DoMWoB project (see Acknowledgement). Within the scope of the project, the design, construction, testing, and finally market research of DMWBE in multi-story constructions will be provided.

Geometrically original and structurally-sound digital models and built prototypes; laboratory tested and optimized prototypes in terms of structural, fire, sound insulation, and moisture transfer resistance & airtightness, and finally, finding out a proper production plant for DMWBE are among expected outcomes mainly through technical performance laboratory tests as well as architectural and structural design software.

This approach incorporates traditional techniques and advanced research, eliminates the use of toxic adhesives and metal fasteners, and leads to better reusability and recyclability, availability, and faster processing of wood for large-scale production (Ilgın et al., 2021b). It would also contribute to the uptake of DMWBE for more diverse and advanced structural applications and subsequently yield both environmental and economic benefits.
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 3) as well as Japanese and Korean traditional buildings (Sumiyoshi and Matsui, 1990; Pang et al., 2011). Besides these, this technique was utilized in Chinese ancient architecture (Zhang et al., 2018; 2019), 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 (Yingzao Fashi, 1998). 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 (Rivers and Umney, 2003). In Europe, the dovetail joint is also called a swallowtail joint, a culvertail joint, or a fantail joint (Routledge French Technical Dictionary, 1994).

Figure 3. A stone pillar (Source: Wikipedia)
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 (Jasieńko et al., 2014). Notable examples of connecting the roof rafter and beams involved in making use of the dovetail joint were churches in the 14th century (Jasieńko et al., 2014). 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. Moreover, as Polish churches, the Church in Cewków (Figure 4) and the Church in Chotylub 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 the mid-20th century (Tannert et al., 2012). Different dovetail designs in Europe and Asia often govern practical considerations. However, high labor costs and inadequacies due to excessively traditional designs rendered these joints uncompetitive. Advancements in computer numerical control (CNC) wood processing machines re-established the cost-effectiveness for carpentry-type wood-to-wood joints.

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 (Chiniforush et al., 2018; Toivonen and Lähtinen, 2019; Mohd Yusof et al., 2019; Li et al., 2021). However, there is a limited number of studies (e.g., Drdácký and Urushadze, 2019) 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 (Ilgin et al., 2021b).
Among these most prominent studies conducted in the last decade, Jeong et al. (2012) scrutinized the effects of geometric variables on the mechanical behavior of dovetail connection (Figure 3) through finite element method analysis together with experimental tests. 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.

![Figure 3. The dovetail joint for the test specimen](image)

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. (2012) 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 4). 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. (2012) presented various reinforcement methods (e.g., with self-tapping screws, with adhesive layer) to enhance the structural performance of rounded dovetail joints (Figure 5) under static short-term shear loading. 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 (2015) built folded thin shell prototype consisting of timber panels by utilizing automatic fabrication of cabinetmaking joints, i.e., dovetail joints without adhesive (Figure 6). This interlocking arch prototype was constructed from 21mm LVL...
panels and 12mm 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. (2014) 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. Similarly, Pozza et al. (2015) 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). 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 the material and failure behaviors without considering the effects of material properties and geometric configurations (Jeong and Hindman, 2009; Jeong et al., 2010; Park and Lee, 2010).

**RESEARCH METHOD**

To generate geometrically original and structurally sound digital models, and built prototypes of DMWBE, architectural and structural design software will be utilized. After that, with the help of a wood factory in Finland, designed models will be turned into prototypes. As a next step, performance tests on structural properties, fire, sound insulation, and moisture transfer resistance and airtightness will be conducted at the University of Tampere and Turku University of Applied Sciences in Finland. Finally, national, and international timber construction organizations will be visited to meet with stakeholders (e.g., construction industry representatives, timber suppliers, public authorities) to find the right position for DMWBE in the current timber construction market in Finland and Europe.
CONCLUSION

This study aims to create higher value-added circular economy opportunities to increase the competitiveness of Finnish large-scale industrial timber structures at the local level and to support European climate policy as part of bio-economy and sustainable development.

To date, state-of-the-art DMWBE has only been examined on a member basis, or at most at the small-scale prototype level from a limited structural point of view, and mostly from a standpoint. theoretical framework. The literature on ‘DMWE’ is based on insufficient structural analysis and model testing of various connection details, rather than evaluating the performance of a structural component.

At present, although the uptake of DMWBE with adhesive and metal connector-free properties for commercial and structural applications is limited due to new research, for example, DoMWoB (Dovetailed Massive Wood Board Elements for Multi-Story Buildings) (see acknowledgments) (Figure 7), this innovative dovetail concept can be further used in multi-story construction.

![Figure 7. Dovetail massive wood board elements](image)

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