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MEASURING FIRE SAFETY PERFORMANCE: A COMPARATIVE EXPERIMENTAL STUDY ON DOVETAIL MASSIVE WOODEN BOARD ELEMENTS AND CROSS-LAMINATED TIMBER

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ABSTRACT: Adhesives and metal connectors play a critical role in the content of engineered wood products (EWPs). Though, the usage of adhesives can create challenges in terms of sustainability and recyclability because of toxic gas emissions. Metal fasteners are also critical to EWPs, but adversely affect end-of-life disposal, reusability, and recyclability. There is an alternative that is entirely pure wood, dovetail massive wooden board elements (DMWBEs) without adhesive and metal fasteners. In this paper, an experimental comparative fire-resistance study with cross-laminated timber (CLT) was conducted. Model scale test samples of 200 mm thickness, 950 mm width, and 950 mm length for CLT and DMWBE were tested in vertical position according to EN 1363-1. The charring performance of the DMWBE was found to be very similar to solid timber the charring rate being only slightly higher than that of solid timber. The char front was located in the third of the five lamella layers, but no flames or hot gases were observed on the unexposed side. With the tested lamella thickness, dovetail detail was able to effectively prevent the char fall-off. CLT specimens had a clear increase in the charring rate value due to the char fall-off of the first lamellae layer.

KEYWORDS: dovetail massive wooden board elements, CLT, fire safety, char depth, charring rate

1 INTRODUCTION

Owing to its numerous technical benefits e.g., uniform strength, stiffness, dimensional stability, and ecological properties, EWPs have been gradually used in the building sector as a construction material since the 1990s. They are getting more and more competitive in tall building construction [1] as in the 87-meter-high Ascent in Milwaukee (Figure 1) and the 85-meter-high Mjøstårnet in Brumunddal (Figure 2).

Figure 1: *Ascent*
(Photo courtesy of Thornton Tomasetti)

Figure 2: *Mjøstårnet*

Adhesives and metal connectors, with the regulation of the building sector, are frequently utilized as a connection in EWPs for modern wooden structures substituting traditional timber-to-timber assemblies. In this sense, adhesive bonding is among the essential parameters, and adhesives play a crucial role in EWPs, particularly by assisting to preserve the timber, enabling the building to be robust and light, and preventing shrinkage and expansion by natural humidity. But the usage of adhesives can create problems in terms of sustainability, recyclability, and broader ecological effect because of toxic gas emissions including VOC and formaldehyde during their lifetime [2]. Furthermore, in spite of

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continuing developments in this study field, important questions remain about environmentally friendly bio-based adhesives. Metal fasteners are also critical to EWPs, but adversely affect end-of-life disposal, reusability, and recyclability [3].

There is an alternative that is entirely pure wood, dovetail massive wooden board elements without adhesive and metal fasteners (Figure 3). To date, many types of research have been conducted on the technical characteristics of timber with numerous construction solutions based on the usage of EWPs in the literature. However, there is limited research on DMWBEs, and the literature about DMWBE is based on quite a few structural analyses of connection details rather than even assessing the performance of load-bearing elements such as floor slabs [4,5]. This precludes our understanding of the potential of DMWBE, particularly in terms of environmental effects and recyclability [6].

***Figure 3**: Dovetail wall connection*

This study examines dovetail massive wood board elements. They are made of wood lamellae connected using one of the oldest joint techniques. This manufacturing technology offers an adhesive- and metal-connector-free solution from which no harmful chemicals are released [7]. As this is a new solution, very limited information is available on the technical and structural performance and more research is needed in some areas e.g., dimensional stability [8,9]. Within the scope of the DoMWoB project *(Dovetailed Massive Wood Board Elements for Multi-Story Buildings)* (see Acknowledgment), technical performance tests (fire resistance, structural performance, moisture transfer resistance, airtightness, and sound insulation tests) were planned to develop DMWBE for the international market as a replacement for traditional EWPs.

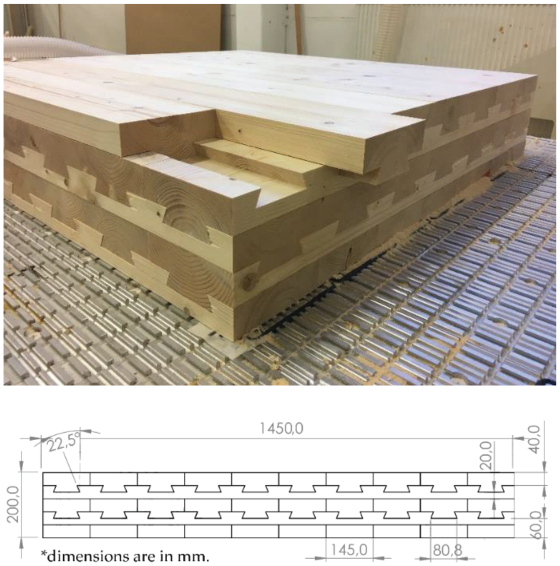

***Figure 4**: DMWBE prototype as fire resistance test specimen*

An ongoing research project at Tampere University is aiming to investigate the performance of DMWBE structures at normal temperatures and when exposed to standard fire conditions. In this paper, an experimental comparative fire-resistance study with CLT was conducted as one of the important stages of evaluation of DMWBE's technical performance within the scope of the DoMWoB project. Model scale test samples of 200 mm thickness, 950 mm width, and 950 mm length for CLT and DMWBE (Figure 4) were tested according to EN 1363-1 [10] in vertical position.

The basic charring rate of a solid timber member made of pine or spruce is typically defined as 0,65 mm/min [11]. For CLT structures the charring rate values depend on many different parameters. The rate values are typically higher than that of solid wood as all the adhesives used are not able to prevent heat delamination and char layer fall-off when the char depth passes the bond lines between laminations. In DMWBE structure no adhesive is used and dovetail detail is used to prevent premature char fall-off.

In this research two fire tests have been conducted on DMWBE and CLT specimens with similar lamellae thicknesses. The study aimed to investigate if the dovetail detail can prevent the delamination of the DMWBE structure during a fire and how well the DMWBE structure maintains integrity and prevents the passage of flames and hot gasses through during the test. Also, charring rate estimates based on the temperatures measured inside the specimens were determined. The results and observations were compared with the results of the CLT specimens manufactured using a polyurethane adhesive. These experimental tests and the main conclusions were introduced in this paper.

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2 FIRE TESTS

This section describes the fire test performed on DMWBE and CLT panels at the Fire Laboratory of Tampere University, considering char depth and charring rate.

2.1 TEST SPECIMENS

2.1.1 Dovetail test specimens

DMWBEs were produced at Vocational College Lapland (Ammattiopisto Lappia), Kemi, Finland [12]. A 5-axis CNC machine (Figure 5) with NUM operating system and compatible SOLIDWORKS computer application was used to manufacture the two test specimens. CNC post-processor methodology was employed, creating a unique integrated environment for the individual steps of finishing, toolpath optimization, and G-code simulation for manufacturing [13]. The moisture content of dovetail boards at the time of manufacture was between 10-12%. On the other hand, the relatively long production time due to the lack of a mass production line and the need for different types of tools such as blades and the removal of dust were the main challenges encountered during production.

Figure 5*: 5-axis CNC machine used in DMWBE manufacturing at Vocational College Lapland (Kemi, Finland)*

To explore the fire resistance of DMWBE, two separate boards were manufactured. Each board was produced 200 mm thick, 1015 mm wide, and 1450 mm long (Figure 6), then cut into dimensions 200 mm thick, 950 mm wide, and 950 mm long. The boards were manufactured from Norway Spruce with C24 PS strength class. The moisture content of the test specimens at the time of the test was 10,3 %.

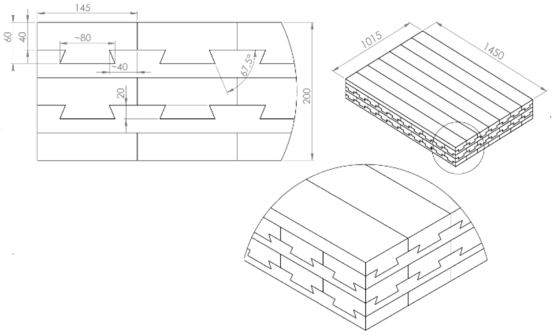

Figure 6*: DMWBE test sample production drawings*

2.1.2 CLT test specimens

CLT panels were manufactured at CLT Plant Oy in Finland [14] for comparison with DMWBE. To explore the fire resistance of CLT, two separate panels were tested, and each test was performed on a panel 200 mm thick, 950 mm wide, and 950 mm long (Figure 7) as in DMWBE. The dimensions of a lamella were 145 mm by 40 mm. The adhesive used in CLT panels was M1 class polyurethane adhesive and lamellas supplied by Kiilto Oy (Tampere, Finland), where the adhesive was applied to all four faces of a lamella. The boards were manufactured from Norway Spruce with C24 PS strength class.

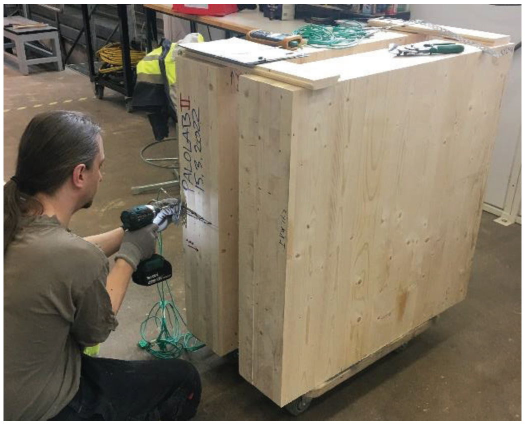

Figure 7*: Preparation of CLT specimens for fire resistance test at Tampere University Fire Laboratory (Tampere, Finland)*

3 TEST SET-UP

In each test, two specimens of similar construction were mounted to supporting construction, made of aerated concrete blocks, in vertical position, as shown in Figure 8. The specimens were installed with their outer lamella layers in vertical direction.

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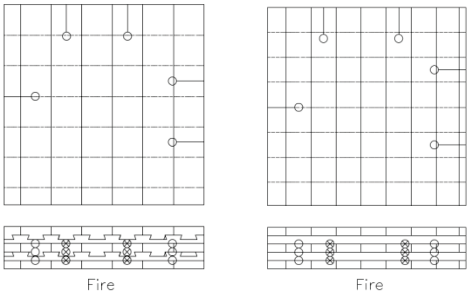
***Figure 8**: Specimens mounted to supporting construction made of aerated concrete blocks. (Unexposed side)*

The tests were conducted according to EN 1363-1 (2020). During the test, furnace temperature, specimen temperatures, oxygen content within the furnace, and pressure differences between the furnace and test hall were monitored. The pressure was set to 20 Pa at the level of the specimen's top edge. The oxygen concentration in the middle of the furnace chamber was measured using a Dräger EM200-E multi-gas detector.

The char depth and charring rate assessments were based on temperatures measured inside the specimens during the test. Since the main aim of these tests was to observe the performance of the new non-adhesive construction in fire conditions and to investigate if the dovetail detail can restrict the delamination of the panels, it was considered that temperature measurements at main lamella interfaces only provide sufficient information. In a specimen, five thermocouples were used to monitor temperatures on one interface between two lamella layers. Schematic diagrams of the placement of the thermocouples in DMWBE and CLT elements are shown in Figure 9. In the vertical section of the slab, these thermocouples overlapped with the other thermocouples at different lamella interfaces. Shielded 3 mm diameter Type-K thermocouples were installed into 3,5 mm diameter holes drilled from the side face of the specimen and 150 mm along the interface between the layers.



a) b)

***Figure 9**: Elevation and cross-section of the CLT specimens and positions of the in-depth thermocouples: a) DMWBE and b) CLT panels.*

4 TEST RESULTS

Both tests were terminated, and the burners were shut off 140 min after the commencement of the test. The furnace temperature followed the standard temperature-time curve [10]. In both tests, the oxygen content in the furnace chamber was around 5 % during the first 60 minutes as seen in Figure 10. This is when the first lamella layer had charred through. In the case of DMWBE, the oxygen content decreases steadily thereafter, being approximately 2,5 % at 120 minutes. In the case of CLT, the oxygen content drops down to zero very rapidly at 65 minutes and remains for 15 minutes at this low level. Visual observations through the furnace camera showed that at the same time, large areas of the first lamellae layer fell off. After this, the content quickly increased again to 4 % and remained at this level until 117 minutes, after which the concentration decreased again to zero. This corresponded well with the visual observations of the falling off the second lamella layer.

The observations showed that both of the panel products were able to prevent the passage of flames and hot gases through the structures. In all the specimens, the char front was located in the third lamella layer at the end of the test, i.e. at 140 minutes.

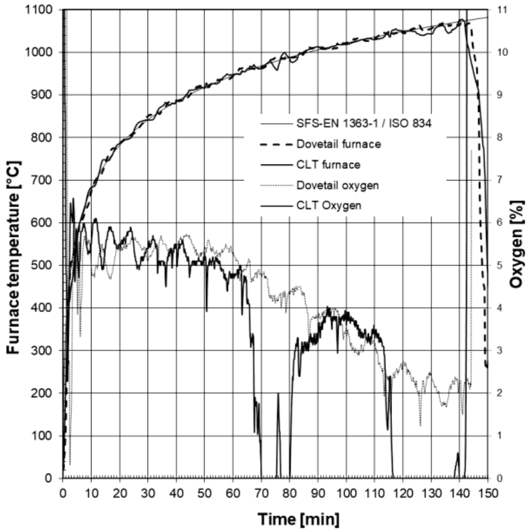


***Figure 10**: Furnace temperatures and oxygen concentrations measured during the fire tests.*

The char depths of the panel product were based on temperatures measured inside the specimen during the test; the charring temperature of the wood is considered to be 300 °C. Figure 11 illustrates the mean charring depths interpreted for the DMWBE and CLT panels. Also, the charring depth development based on the design charring rate of 0,65 mm/min for solid timber is shown in Figure 11. The results showed that the charring performance of the DMWBE panels corresponds well to the charring performance of solid wood, while the charring rate of the CLT panels starts to increase due to the char fall-off of the first lamella layer at 60 minutes. As the tests were terminated before the char front had reached 120 mm at

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any thermocouple location, the mean charring depths can be determined only up to the point, when the temperature of a thermocouple at 80 mm first exceeds 300 °C. This is why the curve representing the mean charring depth for the CLT panel stops at 86 minutes.

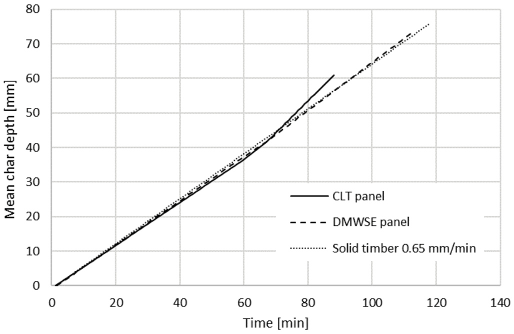

Figure 11*: Mean charing depths for DMWBE and CLT panels. For comparison, charring depth development based on the design charring rate of 0,65 mm/min for solid timber is shown.*

Based on the test results the dovetail structure was able to limit the delamination of the unloaded DMWBE panel during the fire exposure. The estimated average charring rates determined between the exposed face and 40 mm and between 40 mm and 80 mm were 0,65 mm/min and 0,70 mm/min, respectively. The rate values were only slightly higher than that of solid timber. In the first layer, charring rates ranged from 0,57 mm/min to 0,70 mm/min, and in the second layer from 0,52 mm/min to 0,83 mm/min. Figure 12 shows the charred dovetail geometry after the test. In the structure tested, the panels were made of 60 mm thick lamellae. The charring performance can be very different and the charring rates are higher if thinner lamellae are used. In the case of the CLT panel, the charring rate of the first lamella layer was 0,62 mm/min, but when the charring progressed into the second lamella layer, the rate increased to 0,93 mm/min due to the char fall-off. This can be seen in Figure 11, as the curve representing CLT starts to deviate at this point from the curves of solid timber and DMWSE. In the CLT panel, charring rates for the first layer ranged from 0,57 mm/min to 0,69 mm/min, and in the second layer from 0,78 mm/min to 1,36 mm/min.

Uncertainties related to the accuracy of the position of the thermocouples and the thermal disturbance errors induced by shielded thermocouples were not analyzed in this research.

Figure 12*: Remaining lamella layers and the dovetail structure of DMWBE at the end of the test.*

5 CONCLUSIONS

Two fire tests were conducted on DMWBE and CLT specimens with similar lamellae thicknesses to investigate the integrity and thermal insulation properties and charring of the adhesive-free DMWBE structure during a fire. The results and observations were compared with the results of a CLT panel of similar lamellae thickness manufactured using a polyurethane adhesive. The charring performance of the dovetail construction was found to be very similar to solid timber the charring rate being only slightly higher than that of solid timber. At the end of the test, the char front was located in the third of the five lamella layers but no flames or hot gases were observed on the unexposed side. With the tested lamella thickness, dovetail detail was able to effectively prevent the char fall-off. CLT specimens had a clear increase in the charring rate value due to the char fall-off of the first lamellae layer.

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