WORLD CONFERENCE ON TIMBER ENGINEERING 2025
BRISBANE, AUSTRALIA
Advancing Timber for the Future Built Environment

THE INFLUENCE OF ADHESIVES, WOOD SPECIES AND MANUFACTURING TECHNIQUES ON THE FIRE PERFORMANCE OF ENGINEERED WOOD

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ABSTRACT: The fire performance of engineered wood products is crucial to ensure safety and reliability in timber buildings. Key factors such as adhesives, wood species, manufacturing technologies, etc. can impact fire performance significantly. Adhesives with high thermal strength are essential for maintaining structural integrity under fire conditions. The choice of wood species affects density and combustion properties, both important when it comes to the ignition and charring of wood. Different manufacturing techniques can contribute to thermal performance and structural resilience in fire. To ensure accurate predictions of fire resistance, it is crucial to standardize fire testing protocols, considering and controlling as many factors as possible (like moisture content, heat flux, environmental conditions alongside with previously mentioned factors). This research dives deeper into the influence of adhesives, wood species, and manufacturing technologies on the fire performance of engineered wood products. By understanding and controlling these parameters, we can enhance the fire safety of engineered wood products. The three parameters are examined, emphasizing the need for controlled fire testing to compare results and predict the behavior of engineered wood elements in physical buildings.

KEYWORDS: cross-laminated timber, cone heater, shear testing, fire performance, engineered wood

1 INTRODUCTION

1.1 BACKGROUND

The fire performance of engineered wood is a critical property that influences its application in construction and architectural design. Engineered wood products (such as cross-laminated timber (CLT), glued laminated timber (GLT), finger jointed structural timber, laminated veneer lumber (LVL), etc.) are widely used due to their strength, versatility, and sustainability. However, the fire performance of engineered wood products can be a major concern for safety. The fire resistance of engineered wood is affected by innumerable factors, including the technology used in its production, the type and quantity of adhesives, the density of wood, the use of fire-retardant treatments, moisture content and the design of the element. It is nearly impossible to predict all the factors in a test environment. However, it is important to control some of the major factors as much as possible to be able to predict what happens in a fire scenario.

The field of fire testing for engineered wood products is constantly evolving from traditional large-scale fire tests to more efficient small-scale testing methods. One of the advantages of a small-scale method is that small, uncomplicated test specimens allow to observe how changing different factors affect the results.

The influence of adhesives on the bond line integrity has been studied well in ambient conditions. The difference between adhesive families is imminent [1]. The fire performance of adhesives has been previously studied to some extent in large, model and small scale [2]. FIRENWOOD, a transnational research project, dealt with the fire performance of different adhesives in all three scales. The results of the project showed that some adhesives tend to be less effective in fire than others due to the softening of the bond line at elevated temperatures, causing the specimen to fail at a lower strength. It was also concluded that small scale testing gives similar results to large scale and model scale testing [3] - [5]. Zelinka et al. have also demonstrated that the performance of different adhesives varies when exposed to elevated temperatures [6]. It has been demonstrated that the cure conditions of the adhesive also influence the shear capacity of the specimens [7], [8].

The wood species can influence the charring rate of CLT as the charring rate is connected to wood density [9]. The pressure needed for pressing CLT also highly depends on

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https://doi.org/10.52202/080513-0576

the density of wood, as more dense wood needs to be pressed at higher pressure levels [1].

The main manufacturing technologies used today in engineered wood production are vacuum pressing and hydraulic pressing. In ambient conditions, the adhesion may not be impacted as much by these factors, but further knowledge is needed in terms of fire conditions and this work aims to fill in some of this knowledge gap.

1.1 AIMS AND OBJECTIVES

The aim of this work is to observe the influence of the adhesive used, the type of wood species, and the manufacturing technology used on the fire performance of a crossed-laminated timber product. The main objectives of this research are to produce, test and compare twelve different CLT setups with varying wood species, adhesives, and manufacturing technologies. These tests should give an indication on whether and how these parameters affect the fire performance of crossed-laminated timber.

2 MATERIALS AND METHODS

2.1 PREPARATIONS

Test specimens were entirely produced in a TalTech laboratory. Three types of wood species were chosen for CLT production: spruce (Picea abies), aspen (Populus tremula), and black alder (Alnus glutinosa). Spruce was chosen as a common softwood species used in CLT production, the hardwood species were chosen as they were available in the laboratory and due to their potential applications gaining increasing interest worldwide [10], [11]. Two types of adhesives were used for CLT production: PUR (one-component polyurethane) and MUF (melamine-urea-formaldehyde). Specimens were produced using two manufacturing technologies: hydraulic pressing (INFOR PM84) and vacuum pressing (TF 300HV). Twelve 3-ply CLT configurations were produced, each with a dimension of 240 mm x 360 mm and a height of 20 mm + 40 mm + 20 mm. The configurations were as follows (adhesive – species – manufacturing technology):

1) PUR – aspen – vacuum press
2) PUR – aspen – hydraulic press
3) PUR – spruce – vacuum press
4) PUR – spruce – hydraulic press
5) PUR – black alder – vacuum press
6) PUR – black alder – hydraulic press
7) MUF – aspen – vacuum press
8) MUF – aspen – hydraulic press
9) MUF – spruce – vacuum press
10) MUF – spruce – hydraulic press
11) MUF – black alder – vacuum press
12) MUF – black alder – hydraulic press

Material selection followed predefined parameters, prioritizing lumber of similar age and harvesting locations. Efforts were made to select lumber with minimal defects, such as knots, cracks, insect damage, rot, or other imperfections. The selected lumber was stored at 20 °C and RH 48 % for 7 days. The boards were numbered and moisture content for each board was measured. The lumber was processed into boards with cross-section sizes of 20 mm x 120 mm and 40 mm x 120 mm. The board density was determined after weighing the board, the densities varied mostly between 450 – 480 kg/m^3 for spruce, 480 – 560 kg/m^3 for aspen, and 450 – 550 kg/m^3 for black alder. The moisture content of the lumber ranged from 13% to 16%, which was an acceptable range for this study. The cut boards were stored in a conditioned room for an additional 7 days, but the moisture content was not measured a second time.

For CLT production, formwork was prepared to avoid lamellae shifting during pressing. The amount of adhesive applied was established by the adhesive producers: 150 g/m² for PUR and 250 g/m² for MUF (around 40 – 45g and 65 – 70g per panel respectively). The presses were in the same laboratory and the goal was to apply a pressing force of around 1 MPa in both cases to compare the technologies. However, as it turned out during the production phase, the vacuum press reached a pressing force of around 0.8 MPa and due to the age of the hydraulic press, the pressure force varied between 1 and 1.2 MPa. The pressure can be compared, as similar (vacuum presses often operate at way lower pressures). The chosen pressure of 1MPa was suggested by the adhesive manufacturers. Panels were pressed in 20°C at 48% for 60 minutes in all cases as directed by adhesive manufacturers.

Each produced CLT panel was cut into six specimens sized 100 mm x 100 mm x 80 mm. In total there were seventy-two specimens, three of which had defects and weren't used. All specimens were marked with a unique name. The tested glue line surface was reduced to 50 mm x 50 mm by cutting a notch at the bond line on all sides using a thin band saw. The information about each specimen, including wood species, thickness of lamellae, and density of each lamella was gathered in a table.

2.2 TESTS AT AMBIENT CONDITIONS

Twelve specimens were chosen for ambient shear testing. The aim of the test was to evaluate the load-bearing

https://doi.org/10.52202/080513-0576

capacity of face bonds at ambient temperatures (20 °C). An electromechanical testing machine (LFM-600) was used for the shear test. The test specimen (Fig. 1 and Fig. 2) was screwed to an auxiliary board, to avoid movement during the test and allow for deformations during the test.

Figure 1. Test specimen tested at 20°C for shear capacity. Specimen is attached to a horizontal auxiliary board to avoid movement during the test and allow deformations. On top of the lamella closest to the camera the testing machince can be seen, which applies force to the lamella.

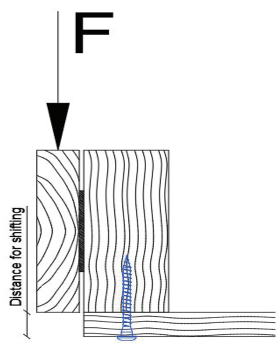

Figure 2. Test set-up for shear tests at ambient conditions [12].

2.3 CONE HEATER TESTS

Thirty-seven specimens were chosen for the cone heater tests. The aim of the test was to evaluate the load-bearing capacity of the adhesive bond at elevated temperatures and fire. Using a small-scale method is beneficial as multiple reiterations can be performed. The specific method used is not standardized but has been described and used in numerous projects where face bonds have been under investigation [3]. The decrease in the load-bearing capacity of an adhesive bond can be evaluated by exposing the bond to heat using a cone heater (ISO 5660) and then performing a shear test immediately once the desired temperature in the bond line has been achieved. A shear testing machine with a minimum capacity of 30 kN was utilized to measure the shear capacity of the bond line.

The specimen was prepared for the test by placing two thermocouples in the notch close to the bond line (Fig. 3). To ensure accurate temperature readings and prevent the thermocouples from being influence by air within the notch, ceramic insulation was placed inside the notch. The specimen is covered on the sides with gypsum board pieces with a thickness of 15 mm, this is necessary to prevent the sides and thermocouples being affected by the heat. The edges of the top surface were protected by 25 mm wide strips of gypsum board pieces with a thickness of 5 mm to ensure a final exposed surface area of 80 mm x 80 mm. The specimen was then placed under the cone heater. A heat flux of 50 kW/m² was applied to the top of the specimen. The heat flux was chosen as it follows the standard fire curve rather closely for the first 30 – 40 minutes [13]. Once the target temperature in the bond line was achieved, the specimen was removed from beneath the cone heater, and the gypsum was carefully removed. The target temperatures varied from 180 °C to 290 °C. The specimen was then subjected to shear loading until failure. The failure mode and shear capacity were documented for each specimen.

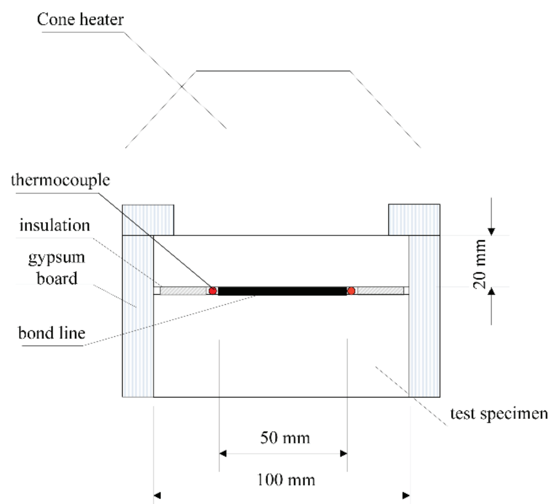

Figure 3. Test specimen geometry and setup under the cone heater. The test specimen is covered with gypsum board pieces, with a thickness of 15 mm on the sides and 5 mm on the top. The exposed surface area on top of the specimen is 80 mm x 80 mm.

3 RESULTS

3.1 TESTS AT AMBIENT CONDITIONS

The results of the shear tests conducted under ambient conditions are presented in Fig. 4. Three specimens made from aspen and black alder exhibited an adhesive failure mode; these are the specimens with the lowest shear capacities shown in the graph. It can be observed from the graph that the shear capacities for the rest of the

https://doi.org/10.52202/080513-0576

specimens are closely correlated with the density of the wood, with hardwoods exhibiting higher shear capacities, as expected.

3.2 TESTS AT ELEVATED TEMPERATURES

The tests at elevated temperatures showed scattered results. The influence of the three parameters—adhesives, wood species, and manufacturing technologies—is analysed separately by isolating one parameter at a time while keeping the other two constant. For example, to evaluate the impact of adhesives, specimens with the same wood species and manufacturing technology are compared to determine whether different adhesives yield similar or varying results.

The influence of wood species on the bond line integrity in fire is not distinctly observable. No clear trends emerge when comparing specimens made with the same adhesive and manufacturing technology but different wood species. Wood species primarily influence the charring rate, as denser woods generally char more slowly, but charring rates weren't analyzed in this study.

Interesting observations can be made when analysing the influence of adhesives and manufacturing technologies by comparing the specimens. Perhaps the most noteworthy are those with spruce, as it is widely used in CLT production. Fig. 5 and 6 show the results of tests on spruce specimens bonded with PUR and MUF adhesives, respectively. In the graphs, the letters A, C, and W following the manufacturing technology indicate the failure mode of the specimen: A represents adhesive failure, C represents char failure, and W represents wood failure. For specimens bonded with PUR adhesive, those manufactured using a hydraulic press exhibit slightly higher shear capacities than those made with a vacuum press. Conversely, for specimens bonded with MUF adhesive, the vacuum-pressed specimens demonstrate higher shear capacities than those produced with a hydraulic press. It is important to note that there was a

slight difference in the pressures used for the manufacturing technologies. One theory for the difference is that the absence of air and moisture in the vacuum pressing process may partly account for the lower shear capacities observed in specimens bonded with PUR adhesive.

When comparing manufacturing technologies and adhesives, the trends differ for the different wood species. At this point, it is not possible to propose a correlation factor between the two manufacturing technologies. It is possible that wood species with higher densities would need higher pressure levels for pressing.

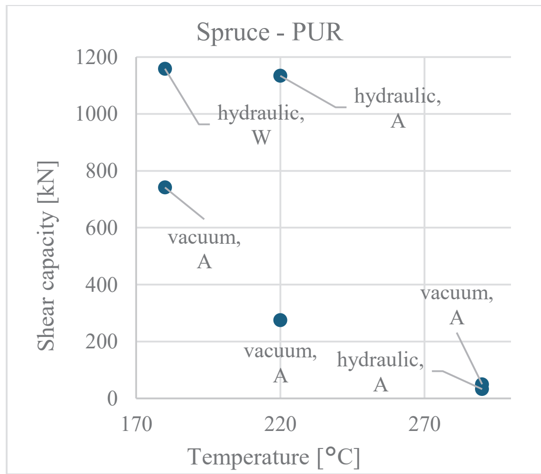

Figure 4. Shear capacity of spruce specimens bonded with PUR adhesive at different temperatures. The data includes specimens manufactured using hydraulic and vacuum technologies, with corresponding failure modes indicated.

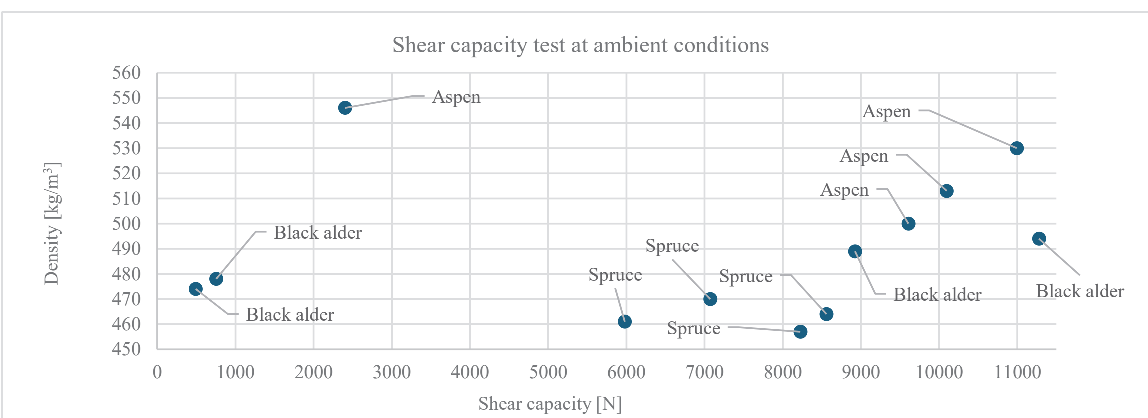

Figure 4. Shear capacity at ambient conditions

https://doi.org/10.52202/080513-0576

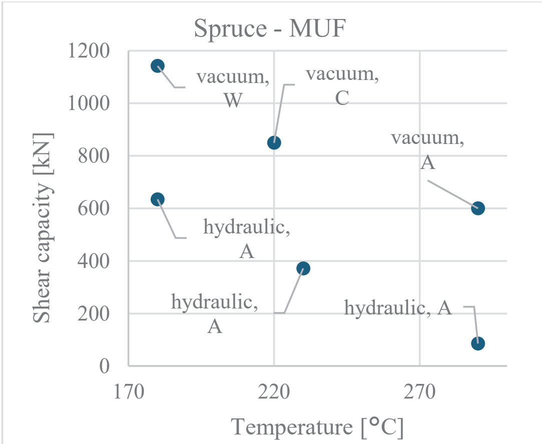

Figure 6. Shear capacity of spruce specimens bonded with MUF adhesive at different temperatures. The data includes specimens manufactured using hydraulic and vacuum technologies, with corresponding failure modes indicated.

4 CONCLUSIONS AND RECOMMENDATIONS

At ambient conditions the influence of adhesives or manufacturing technologies is not clear. The shear tests yield predictable results, as shear strength increases with increasing density.

The tests conducted at elevated temperatures show that using different manufacturing technologies can lead to varying shear capacities under these conditions. These results are also influenced by the specific adhesive used. However, the effect of wood species on the results is not distinctly observable. While no clear correlation between the technologies is apparent, a difference between hydraulic and vacuum pressing becomes evident when the pressures are similar. It is important to note that vacuum presses in the industry often operate at lower pressures, which may further impact the results. To validate this, additional testing at elevated temperatures is required. For example, varying pressure levels could be tested to explore the correlation between vacuum and hydraulic pressing.

It is worth further investigating how the adhesive bond lines in CLT behave when pressed with different technologies. While there may be no significant influence at ambient temperatures, it appears to play a role at elevated temperatures.

ACKNOWLEDGEMENTS

The research was funded by the European Union and Estonian Research Council via project TEM-TA80 and by the Estonian Research Council Grant PRG2213.

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https://doi.org/10.52202/080513-0576