Effect of surface treatments on the bond quality of laminated OSB products

by

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Bachelor of Science in Engineering (Wood Science and Engineering), Nanjing Forestry University, P. R. China, 2018

A Report Submitted in Partial Fulfillment
of the Requirements for the Degree of

Master of Forestry Engineering

in the Graduate Academic Unit of Forestry and Environmental Management

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This report is accepted by the Dean of Graduate Studies

THE UNIVERSITY OF NEW BRUNSWICK

August 2019

ABSTRACT

The ultimate objective of this thesis report was to develop a new type of lumber-like wood products made of OSB sheets, i.e. laminated OSB (LOSB). The specific objective of this thesis report was to investigate the optimized surface treatment parameters on the bond quality of LOSB, including sanding and grooving. This project used 6 surface treatment methods and 2 adhesives [phenol formaldehyde (PF) and isocyanate] to fabricate 2-layer LOSB specimens by considering 2 panel directions (major and minor). 3 types of tests were conducted, center-point short-span bending test, block shear test and percentage wood failure (PWF). A total of 768 specimens were fabricated. It was found that: (1) The best bond quality of LOSB specimens was, in terms of horizontal shear strength, block shear strength and PWF, obtained at combined surface treatment, i.e. sanding and tooth-plate indenting, which was bonded using PF. (2) The specimens had a 10-30% and 5-40% higher bond horizontal shear strength and block shear strength in the major direction than in the minor direction, respectively. (3) The average horizontal shear strength and block shear strength of the specimens from the central positions were about 4-8% and 3-10% larger than those from the edges, respectively. (4) The surface treatment, panel direction, and adhesive type had a statistically significant impact on the horizontal shear strength and block shear strength at a 95% confidence level. (5) The average values tested for horizontal shear strength and block shear strength were 2.25MPa and 4.4MPa, respectively. (6) The combination of sanding and tooth-plate indenting could be a good surface treatment to increase the bond strength.

Key words: OSB, Laminated OSB, bond quality, block shear strength, horizontal shear strength, percentage wood failure, surface treatment, sanding, tooth-plate indenting.

ACKNOWLEDGEMENTS

I would first like to thank my thesis supervisor Dr. Meng Gong. He consistently allowed this thesis to be my own work, but steered me in the right the direction whenever he thought I needed it. Dr. Gong not only provided me with a lot of academic advices, but also taught me with all his patience and inspired me to work harder and harder. I am very appreciative of all the help Dr. Gong provided in my studies and daily life, and his teachings encouraged me when I was alone in a foreign country.

I would also like to thank Dr. Xin Guan (my co-supervisor), Dr. Ling Li (my supervisory committee member), Mr. Zizhen Gao (my PhD brother) and Ms. Jennifer Xiao. They helped me design the experiment and write a rigorous thesis. I would like to acknowledge Mr. Dean McCarthy and Mr. Greg McCarthy who helped me set up the experiments and encouraged me to put all my passions into this project.

I want to thank Arauco's contributions in terms of the OSB panels and PF adhesive alongside support from the New Brunswick Innovation Research Chair Program, New Brunswick Innovation Foundation, and the 3+1+1 program between the University of New Brunswick and Nanjing Forestry University.

Finally, I must express my very profound gratitude to my parents and to all my friends for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis. This accomplishment would not have been possible without them. Thank you.

Zeyu Ma

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1 Introduction

1.1 Project background

As a renewable natural material, wood has been widely used in various industries. However, due to the anisotropic nature and various growth characteristics of wood, more stable and stronger wood products should be invented. Engineered Wood Products (EWP) could be a good choice for replacing some metal or concrete structural elements because of its good mechanical properties. Oriented Strand Board is also a member of the EWP family and it is widely used for sheathing and flooring. It is necessary to test its quality and then apply it to various fields. Evidently, of wood for structural timber, the detection of wood quality and its quality grading are key technical tasks to achieve the best use of wood.

Oriented strand board (OSB) is an engineered structural-use panel manufactured from thin wood strands bonded together with water-resistant resin, typically Phenol formaldehyde (PF) or Polymeric diphenylmethane diisocyanate (pMDI) (Ross,2010). OSB is a structural panel that competes directly with softwood plywood in many construction applications, particularly among exterior wall and roof sheathing and nearly half of all floor decking (McKeever, 1997).

Wood recovery would decrease with the increasing of log diameters. Wood recovery from the making of plywood from logs is as low as 50%, meanwhile that from the making of OSB could raise to more than 90% due to the small size of chips used to manufacture OSB panels (Matt, 2006). Today, a wide range of high quality and innovative wood building materials are manufactured. Their performance and relative economic advantage signify that wood products are unrivalled as principle structural materials for residential construction. Wood products are also extensively used in the construction of commercial, industrial and institutional buildings. In North America, wood products dominate the structural framing and sheathing of the residential construction market. There are also many examples of public, commercial, and industrial buildings that have been constructed using wood products as the principle structural material (CWC, 2019). It is estimated that panel products (e.g. plywood, OSB, particle board and medium density fiber board) account for 15 percent of the energy used by the wood product sector. Also, OSB accounts for a large share of the market for sheathing and sub-floor underlay, becoming more popular than plywood, commanding 66% of the structural panel market (Marotte and Bertrand,2016). However, because of its lower dimensional stability when exposed to moisture, it has not completely replaced plywood (Semple et al., 2009).

1.2 Manufacturing and Applications of OSB

OSB is widely used for door, floor, and other construction elements. High-density species, such as beech and birch, are often mixed with low-density species, such as aspen, to design and produce panel properties (Bowyer et al., 2007).

Figure 1.1 provides an example illustrating the manufacturing of OSB. The logs are debarked after being soaked in a heated pond. Strands are cut from the debarked logs in dimensions up to 150 mm (6 in.) long. The strands are put into bins and dried until the appropriate moisture content is reached. After they are dry, the strands are blended with resin binders and wax, which improves the efficiency of the resin binder and enhances the panel's resistance to moisture absorption. Strands go through a forming line where cross-directional layers are formed. The layers are pressed together under intense heat and pressure to form a rigid, dense structural panel. The OSB panels are cooled, cut to size, graded, and edge-coated (Meil et al, 2009). This process of manufacturing OSB is different from other commonly seen engineered wood products. Wood strands typically have an aspect ratio (strand length divided by width) of at least 3. Meanwhile, OSB panels are usually made up of three layers of strands, with the outer faces having longer strands aligned in the long direction of the panel and a core layer that is counter aligned or laid randomly using the smaller strands or fines (Ross, 2010). Some protector will also be sprayed on the surface to counteract the swelling ability of wood.

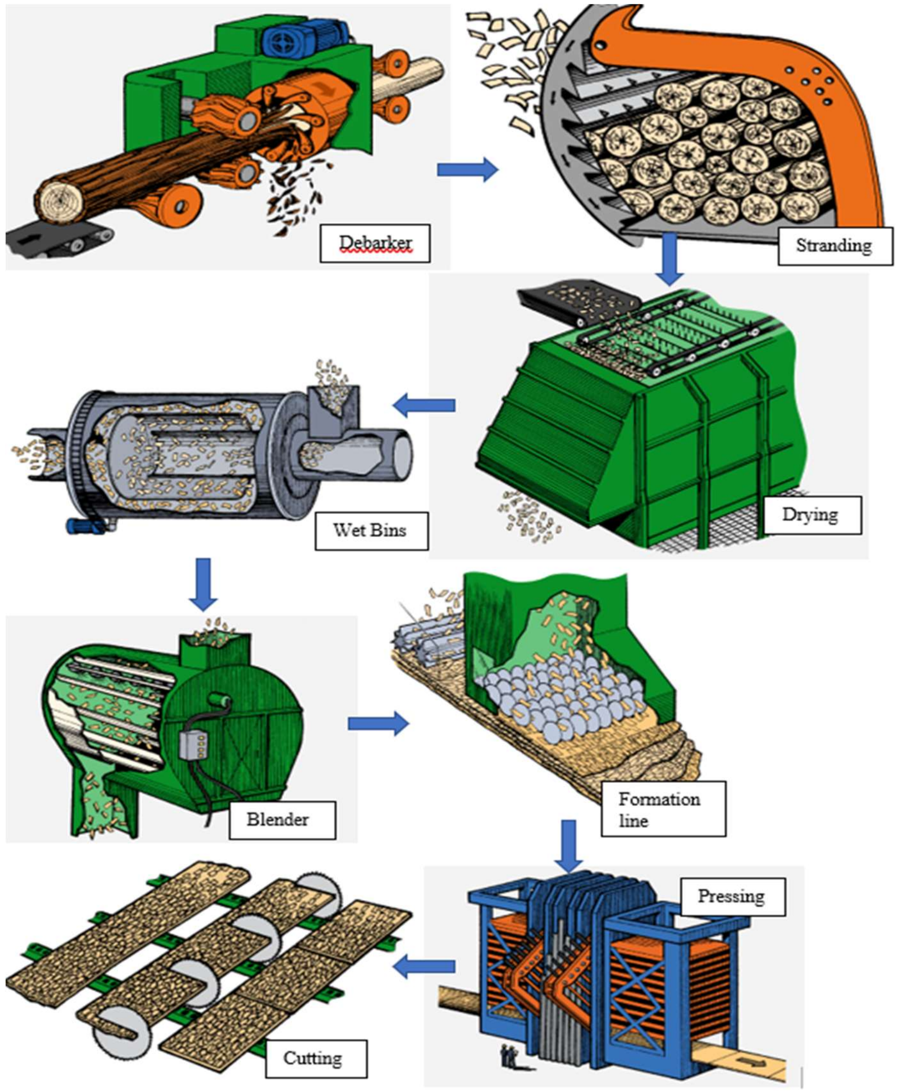


Figure 1.1 Part of Arbec OSB production line (Sourse: https://www.arbec.ca/en/products/manufacturing-process)

The most commonly available sizes of an OSB panel are between 4' (1.22m) wide, 8' (2.44m) long, and 1/4-23/32" (6.35-18.3mm) thick. Due to its smaller size, OSB is more widely used as sheathing materials in building construction and is never used as beams and columns, where glue laminated timber, laminated veneer lumber, laminated strand lumber, parallel strand timber, cross laminated timber and other engineered wood products are employed. In contrast, Plywood, the competing product of OSB, has appeared in another form, i.e. laminated plywood products, which have been used for making beams and columns. If OSB can be laminated to produce a thicker product, its applications can be expanded.

1.3 Laminating of OSB

1.3.1 Surface activation of OSB

Surface activation of a material is a critical factor governing adhesion properties and furthermore bond quality. Activation is represented as surface adhesion properties, which can be achieved by increasing the surface energy of the material, making it more hydrophilic. This increases the surface wettability and renders the surface adhesive (Plasma technology Inc., 2007). Wettability is the ability of a liquid to maintain contact with a solid surface, and it is controlled by the balance between the intermolecular interactions of adhesive type (liquid to surface) and cohesive type (liquid to liquid) (Moldoveanu, 2016). Chen (1970) examined the relationship between surface wettability and glue-bond shear strength of various tropical woods glued with a urea formaldehyde resin, discovering that the percentage adhesion failure increased with increasing level of wettability in determination of the bond-line strength.

OSB panels are usually made up of three layers of strands, the outer faces having longer strands aligned in the long-direction of the panel (Ross, 2010). Thus, larger sizes of strands are on the OSB panel surface and hot-pressed if adhesive is needed. The sanding process may also be used before storing, not only among OSB products, but also with EWP products. The mechanical properties of the OSB surface will change after manufacturing with changing MC, application of chemical materials, and shape changes of wood strands, etc. The surface moisture content and wettability can also be changed by these processes. The penetration of adhesive will also be affected by manufacturing if more OSB panels are bonded after these procedures.

There is a report for plywood bonding situations based on different moisture content (MC). The best bonding results were obtained in plywood panels with veneers having 4–6% moisture content. Lowest mechanical properties were found for plywood panels manufactured from veneers conditioned to 16–18% moisture content (Aydin, 2006). OSB strands should be managed into a range of 2-5% in order to avoid the effect of changing MC, from which OSB panels have a range of MC of 8-12%.

The contact angle is defined as a substrate plane and the free surface of liquid droplet at the line on contact with the substrate, which can be used to evaluate the surface activation of a material (Forest Products Laboratory, 2010). Hse (1971) reported a correlation between penetration and contact angle for PF and southern pine plywood. The author evaluated 36 formulations in regard to contact angle, cure time, heat of reaction, plywood shear strength, percent wood failure, bond-line thickness, and cure shrinkage. There was no significant evidence demonstrating penetration is related to the adhesive solid contents or formaldehyde-phenol mole ratio. PF adhesive is the most common wood adhesive that is also inexpensive in market.

Adhesive penetration can also be varied according to open assembly time, pressing time, temperature, and consolidation pressure involved in wood-based composite manufacture. Process-induced damage to the wood surface may also influence penetration (Kamke, 2007). The tooth-plates are applied to break the initial panel surfaces and change the adhesive penetration in order to achieve a higher bonding quality.

Adhesive may change the molecular weight distribution, viscosity, solids content, and surface tension of the liquid phase of the adhesive, which can all influence the penetration of wood (Kamke & Lee, 2007). Powdered adhesives, such as powdered PF used in OSB manufacture, must undergo a melt to achieve penetration. Johnson and Kamke (1992), in regard to steam-injection pressing, noted that powdered PF resin remained on the surface of wood strands during the blending process, and was only able to flow and penetrate after heating during hot-pressing. Thus, PF should be used with the hot-pressing method in order to penetrate, even taking into consideration the wood strands on the panel surface that are manufactured by the factory. The hot-pressing during the manufacturing of OSB panels could cause the surface materials carbonized due to the high pressing temperature.

Adhesive penetration influences toughness and ultimate strength of bonded assemblies (White 1977; White et al. 1977) while also contributing to a stiffness in compression and shear (Gindl et al. 2005). Many studies, using a variety of analytical techniques, have examined adhesive penetration in wood (Kamke & Lee, 2007). The effect of resin penetration on bond performance and microscopic detection of adhesive penetration in wood were discussed by Kamke (2007). Hare and Kutscha (1974) examined adhesive penetration and shear strength of spruce plywood bonded with PF. Drying technique and the influence of aging were parameters in the study. They noted a deeper penetration into the veneer that had more severe surface damage (cell-wall fractures). This condition was associated with low shear strength, but high percent wood failure. However, Sernek determined that hydrodynamic (sometimes called bulk) flow was the dominant factor for the penetration of UF resin into beech (2007). The application of a clamping force of 1.6 MPa to the bond-line produced a penetration that was approximately 10 times greater than the penetration that was achieved when no force was applied (Kamke & Lee, 2007). Applying a force or pressure might increase the shear strength which is affected by the drying technique and aging. The pre-lab is using the hot-pressing technique and the pressure is around 100psi (0.7MPa). The surface activation of OSB panels should be improved prior to bonding laminated products. There are several methods that could be chosen for activating the surface of OSB with an aim at increasing the bond strength, these could be sanding tooth-plate indenting and using two different types of adhesives.

In a brief summary, OSB surface activation can be affected by the type of adhesive, and wettability and moisture content of OSB. To ensure a good bond quality of adhesively laminated OSB products, surface treatments should be applied to the surface of OSB prior to spreading of an adhesive.

1.3.2 Evaluation of the bond quality of laminated OSB

Nowadays, the preparation of wood surfaces has been studied, and optimum conditions have been determined (Minford, 1991). Because adhesives work by surface attachment, the adherend's surface qualities are extremely important to the laminated OSB product (Ross, 2010). Good penetration into the wood is a very important aspect of wood bonding. Standards such as ASTM D2559 require a bond formation within the minimum and maximum of the recommended open and closed assembly times (Frihart, 2005). The bondability of wood products like plywood, particleboard, fiberboard, flakeboard, and hardboard is hard to classify categorically. These materials often have polished surfaces from hot-pressing which are different to bond (Ross, 2010). Laminated OSB product can be regarded as another type of laminated wood product, the main difference from other products in the market is that the bonding surfaces are manufactured and there are some adhesives and other materials on them. Wood surfaces should be smooth, flat, and free of machine marks and other surface irregularities, including planer skips, and crushed, torn, and chipped grain. The surface should be free of burnishes, exudates, oils, dirt, and other debris (Ross, 2010). During this pre-lab, the sanding procedure is used to remove the materials exist on the panels' surfaces before gluing the panels together.

The bond quality of laminated wood products is widely evaluated using the block shear specimen stipulated in ASTM D198 (ASTM 2015). For the mechanical properties tested during the lab, the shear strength (horizontal shear strength), the shear strength in the block shear test and the Percentage Wood Failure (PWF) will be considered as the most important standards. Wood for these tests was obtained from local suppliers, with the actual test specimens selected according to the protocol in ASTM D1037. The laminated OSB lumber needs a block-type glue-line shear test to evaluate the strength of bond-line based on the standard ASTM D1037 and a static bending test will also be used to calculate the horizontal shear strength of the laminated product.

The load cannot be applied uniformly to the bonded surface while using a block shear test due to the specimens' shape and testing procedures, and it may cause unreliable failures after applying the load. Recently, short-span bending was applied to evaluate the bond quality by Gong (2019), which could show the horizontal shear strength of the tested specimens. The study reported by Gong et al (2019) was aimed at developing an appropriate test procedure to evaluate the adhesively bond strength of cross-laminated laminated strand lumber (CL-LSL). Three-point short-span bending tests were conducted on two-layer asymmetric CL-LSL specimens (2LasymCL LSL). It was found that failure happened along the bond line of an adhesively bonded specimen under short-span bending, when the horizontal shear strength exceeded its bond line shear strength. Meanwhile, Comparatively, the average bond line shear strength of CL-LSL PVAc is about 15% and 10% lower than that of the LSL itself in the major and minor directions, respectively during the block shear test. (Gong et al, 2019).

In addition to mechanical testing, the bond quality of laminated wood specimens can also be examined by analyzing the depth of adhesive penetration in wood via fluorescence microscopy (Modzel, 2011) and estimating the percentage wood failure. Fluorescence microscopy has been used to analyze the penetration of various adhesive types in plywood (Dougal et al. 1980; Gollob et al. 1985) and in other wood composites (Furuno et al. 1983a; Murmanis et al. 2007; Brady and Kamke 1988; Johnson and Kamke 1992, 2007; Marcinko et al. 1995). After the bending or shear block tests, some samples will be needed to evaluate penetration. The samples should have bonding surfaces that are exposed outside. If the penetration cannot be determined properly due to a lack of testing equipment, the percentage wood failure can briefly be used to evaluate the strength of bonding. Wood failure is often considered to be as important as the strength of the bond. Deep wood failure is easy to observe but determining where and why failure takes place in the bond-line has been difficult (Frihart, 2005). The wood failures should not all exist in the bonding area. When the breaks are almost in the wood, rather than in the glue-line, the manufacturing procedures can be roughly determined through the pre-lab.

In summary, the short-span bending test and block shear test are two widely used methods for examining the bond strength of laminated OSB. Percentage wood failure is another important factor of evaluating the bond quality.

1.3.3 Uses of laminated OSB

(a) *(b)*

Figure 1.2 Laminated OSB used in structure wall.

Laminated OSB has recently been created for structural uses, that is manufactured by bonding four layers of OSB panels. Figure 1.2 is one example showing the potential uses of lamianted OSB products, such as short beams. The two layers of polystyrene foam make OSBLOCK a material with high insulating and acoustic properties and can be easily constructed because of its light weight (OSBLOCK^{TM}, 2019)

To make laminated OSB products, surface activation should be considered including wettability, moisture content, and proper treatment methods to reactivate the surface due to the poor surface activation of OSB panels. A short-span bending test and a block shear test should be applied to evaluate the bond quality of laminated OSB products and deliver comprehensive and reliable results by comparing horizontal shear strength and block shear strength.

1.4 Objectives and Scope of Work

The ultimate objective of this project was to develop a new type of lumber-like wood product made of OSB sheets, i.e. laminated OSB (LOSB), which could be used as load-bearing components such as short beams. The specific objective of this project was to explore the proper methods for re-activating the surface and increasing the strength of a bond line in a laminated OSB specimen. To reach this objective, two commonly used mechanical approaches, sanding and indenting, were applied. A design of experiment (DOE) was developed by considering pressing temperature, pressure and time, types of sanding papers, metal tooth-plate, and types of adhesive. The bond quality of 2-layer LOSB specimens were examined via short-span bending test, block shear test, and percentage wood failure examination. The optimized manufacturing parameters were therefore identified. This phase of research paved a solid route for the next step of lumber-size LOSB specimens manufacturing, which will be conducted by another fellow graduate student.

1.5 Thesis organization

This thesis report includes 5 major chapters. Chapter 1 focuses on the research background with an aim to find a proper method of reactivating the surface of OSB. Chapter 2 provides the details on the materials and methods used in this project, including the parameters of manufacturing 2-layer laminated OSB specimens and design of the experiments. Chapter 3 delivers the methods of evaluating their bonding quality in terms of shear strength and percentage wood failure. Chapter 4 gives and discusses the test results via statistics. Chapter 5 draws the conclusions and presents some recommendations for future work.

2 Materials and Methods

2.1 OSB and Adhesives

The OSB panels were provided by Arbec Forestry Products Inc., Miramichi, New Brunswick, Canada. The sizes of the panels were 12’ by 24’ by 7/16” (3.65m x 7.32m x 13mm). The moisture content ranged from 9% to 12%. These panels were cut using a table saw (Model: 350, Serial: Y 7775, GENERAL MFG. CO. LTD, Figure 2.1) into 48 boards of 12” x 12” (305mm x 305mm) to make laminated OSB specimens for testing.

Figure 2.1 Table saw.

Phenol formaldehyde (PF) and isocyanate (ISO) adhesives were identified and used in this project. The PF adhesive (Resin #: 13B202) was provided by the Wood Science & Technology Center (WSTC), University of New Brunswick, Fredericton, New Brunswick, Canada. ISO adhesive (Brand name: ELMER'S, Westerville, Ohio, United States) and sanding papers were purchased from a building supply store located in Fredericton, New Brunswick, Canada. Some detailed info on these two adhesives is given in Figures 2.2 and 2.3. The metal tooth-plates were provided by Corruven Canada Inc., Edmundston, New Brunswick, Canada. The distance spacing between each two teeth was "0.1-0.4" (2.5-10mm) in width direction and 0.2" (5mm) in length direction.

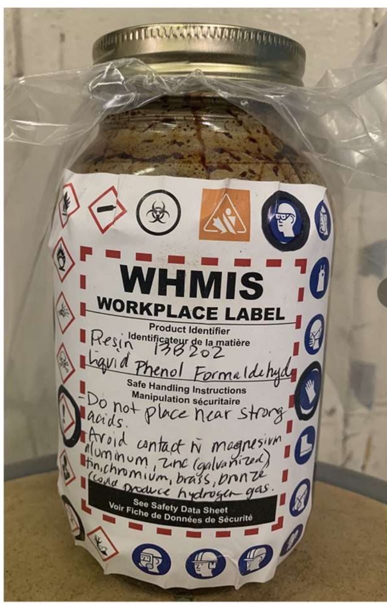


Figure 2.2PF resin Figure 2.3Isocyanate resin

2.2 Surface treatment methods

The surface treatment methods used included sanding, tooth-plate indenting, and a combination of both. Six treatment methods were used, which were (1) plain (without any treatment on the OSB surface), (2) sanding using 100 mesh paper (3) sanding using 600 mesh paper, (4) tooth-plate indenting, (5) tooth-plate indenting plus sanding using 100 mesh paper, and (6) tooth-plate indenting plus sanding using 600 mesh paper.

Figure 2.4 Sanding paper (Source: https://www.lowes.com/n/buying-guide/sandpaper-buying-guide)

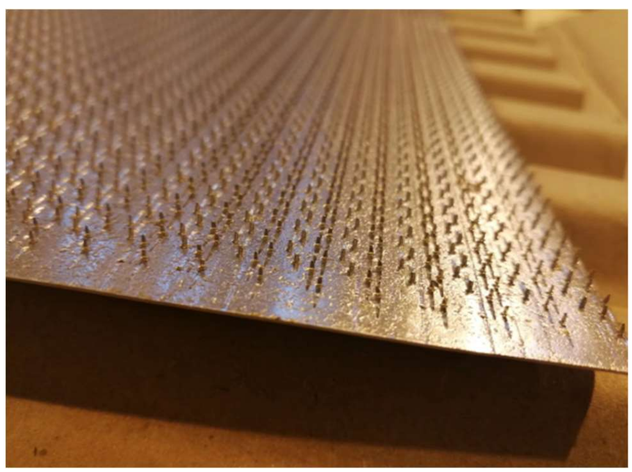


Figure 2.5 Metal teeth on the plate

2.2 Fabrication of laminated OSB specimens

2.2.1 Preliminary study on pressing parameters for making 2-layer specimens using PF

PF is the adhesive that needs to be cured via hot-pressing. To determine the hot-pressing parameters, a pre-lab study was conducted. The press used is called CARVER (Model: #3912), which was available in WSTC. Tables 2.1 & 2.2 show the parameters for hot-pressing and dimensions of glue-laminated panels.

Figure 2.6 Laboratory hot press.

Table 2.1 Hot-pressing parameter test.

Group	Pressure/psi (MPa)	Setting temperature/°C	Pressing time/min		Pressing temperature/°C	
			130 °C	150 °C	200 °C	
P_1	18 (0.12)	200	38	20	15	
P_2	50 (0.34)	200	27	15	11	
			100 °C	120 °C	130 °C	170 °C
P_3	75 (0.52)	150	6.5	10.5		
P_4	100 (0.69)	150	3.5	7.5	11.5	20.5

Table 2.2 Sizes of OSB panels after hot-pressing.

Number		Thickness/mm			Width/mm			Length/mm
P_1	1	23.18	23.50	23.35	38.79	38.51	38.89	139.7
	1’	23.28	23.09	23.12	38.60	38.39	38.55	
P_2	2	21.81	21.80	21.91	38.48	38.55	38.59	
	2’	21.82	22.40	21.82	38.60	38.39	38.63	
P_3	3	22.20	22.36	22.47	38.81	38.57	38.66	139.7
	3’	22.53	22.29	22.30	38.65	38.57	38.80	
P_4	4	21.05	21.23	21.31	38.86	38.84	38.86	
	4’	21.15	21.15	21.10	38.00	36.41	34.72	

2.2.2 Selection of pressing parameters for making 2-layer OSB specimens

According to the preliminary study, the pressing parameters of PF and ISO used in the core study are given in Table 2.3:

Table 2.3 Pressing parameters of PF & Isocyanate resin.

Name	Pressing time/min	Temperature/ °C	Pressure/psi
PF	15	150	100
Isocyanate	15	~ 20	100

The panels were made in the press at room temperature when using ISO and at a temperature of 150°C when using PF. The smooth surfaces of an OSB panel were applied with adhesive and pressed in the press.

2.2.3 Design of experiment

This project provided four options to treat the OSB surface, including: PF resin, Isocyanate resin, sanding paper, and metal tooth-plate. Six surface treatments were given in Chapter 2.2. Two mesh levels of sanding papers (100 mesh & 600 mesh) were used to remove the material on each side of the panels' surfaces. Special metal tooth-plates were chosen to break the initial situation of each panel surface and dig a lot of small holes on bonding surfaces (Pressing machine provided pressure for the tooth-plate. Each panel was carved for 3 to 5 minutes in order to ensure the metal teeth were completely into the bonding surfaces).

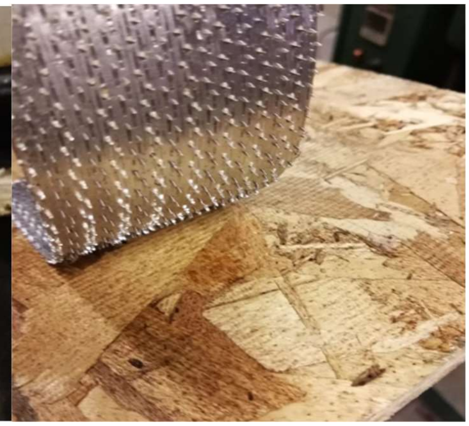


Figure 2.7 Pressing with the metal tooth-plate　　Figure 2.8 Indented panel

Figure 2.9 Full-scale image of 12’’ by 12’’ (305mm by 305mm) indented panel

After the carving and sanding procedure, the preprocessing surfaces were dealt with single gluing by an adhesive consumption of $170g/m^2$. Each bonding surface used 19g of adhesive.

Based on these six methods, each method would be used on eight panels that were cut in the size of 12” x 12” x 7/16” (305 x 305 x 13mm), the example of these panels and the cutting pattern were shown in Figure 2.3.1. After the cutting procedure, two panels were grouped as a 2-layer laminated OSB panel. Thus, each of the six method would be used for creating eight 2-layer product and each of adhesive had 24 2-layer OSB specimens using the six methods, respectively. Specimens should be conditioned to a constant weight and moisture content in a conditioning chamber maintained at relative humidity of 65±5% and a temperature of 23±°C (68±6°F). The removal of materials on the surfaces was applied to each panel and the new type of manufacturing process for Laminated OSB lumber was determined and ready to be tested.

Table 2.2 Details of different Laminated OSB lumber.

Adhesive	Type/Mark	Cutting size Width x Length x Depth
ISO	Plain panel/ IN	12’’ by 12’’ by 7/16’’ (305 x 305 x 130mm)
	Sanding (100 mesh)/ IS1	
	Sanding (600 mesh)/ IS6	
	Tooth-plate/ IT	
	Tooth-plate & Sanding (100 mesh)/ ITS1	
	Tooth-plate & Sanding (600 mesh)/ ITS6	
PF	Plain panel/ PN	12’’ by 12’’ by 7/16’’ (305 x 305 x 130mm)
	Sanding (100 mesh)/ PS1	
	Sanding (600 mesh)/ PS6	
	Tooth-plate/ PT	
	Tooth-plate & Sanding (100 mesh)/ PTS1	
	Tooth-plate & Sanding (600 mesh)/ PTS6	

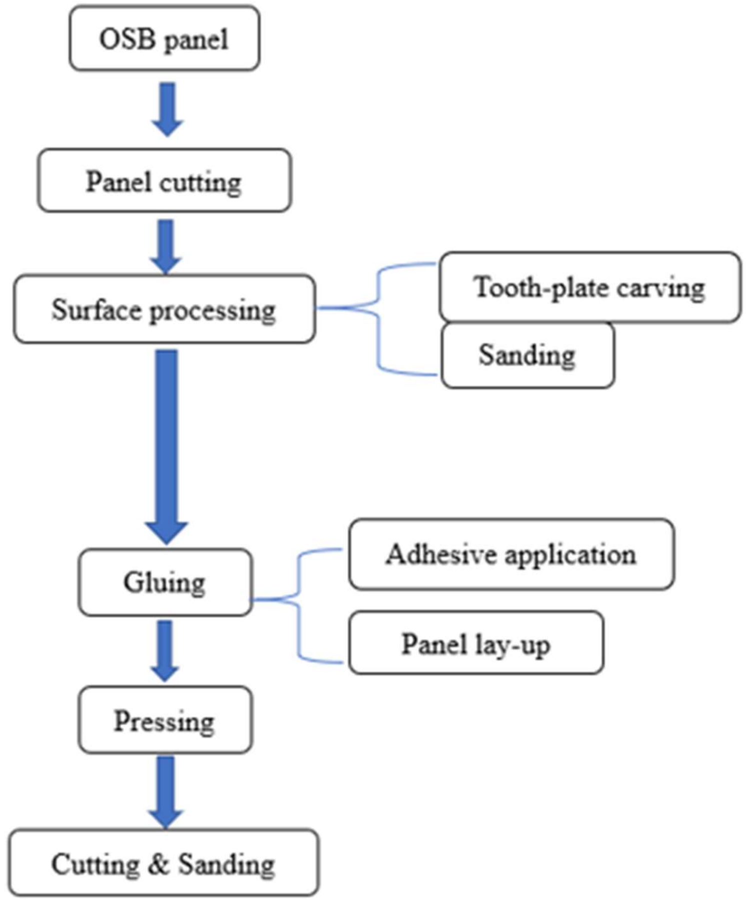


Figure 2.10 Major processes of manufacturing laminated OSB

Table 2.4 shows the groups of laminated OSB lumber with different manufacturing ways. Figure 2.10 illustrates the main part of the manufacturing process used in this project. Figure 2.10 illustrates the major processes of manufacturing laminated OSB with all the surface treatments.

2.3 Manufacturing of short-span bending and block shear specimens

2.3.1 Cutting pattern from 2-layer laminated OSB specimens

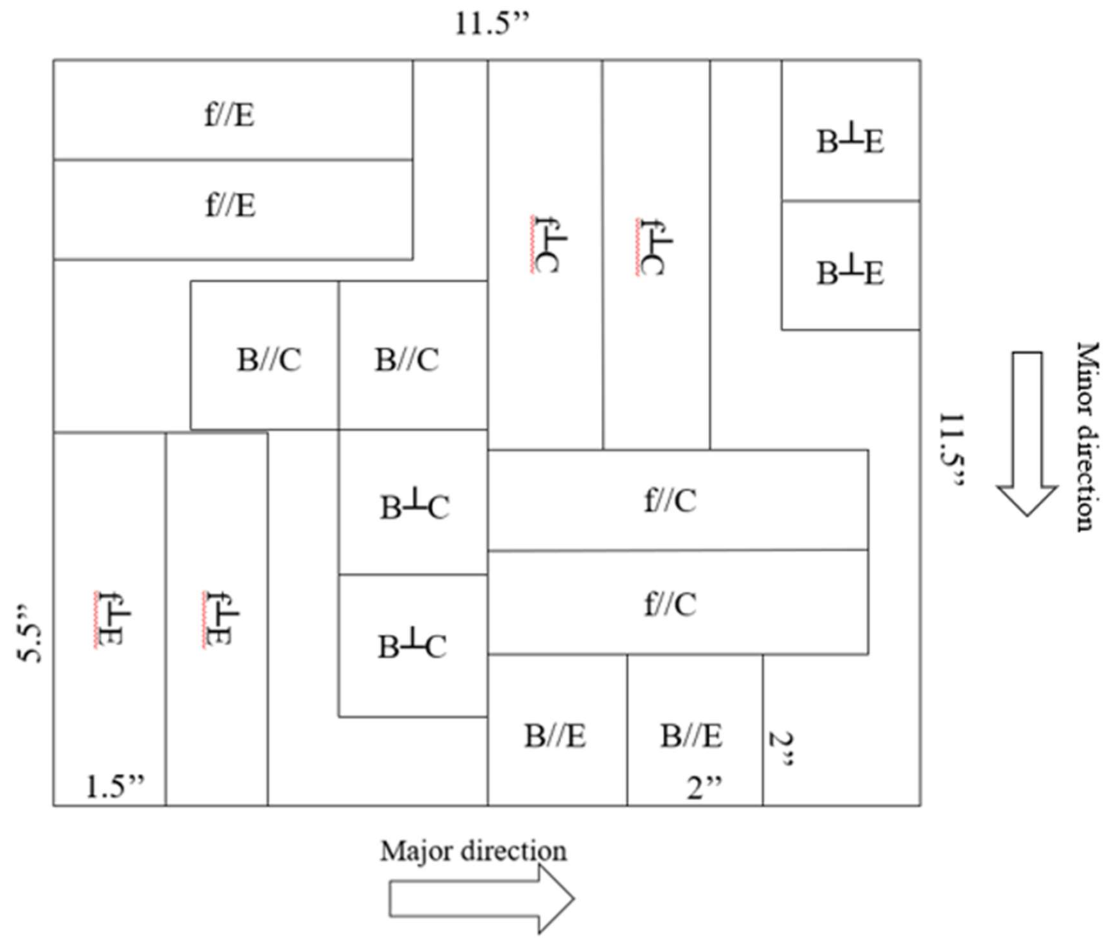


Figure 2.11 The location of each testing specimen in a panel (Note: E: Edge; C: Center; f: short span bending; B: block shear**; // : Parallel to the major direction; ⊥: perpendicular to the major direction**).

The cutting pattern for each 2-layer laminated OSB panel is shown in Figure 2.11, in which there were 8 short-span bending specimens and 8 block shear specimens. For short-span bending specimens, the length direction of a specimen was parallel to the orientation of strands (i.e. the major direction). For block shear specimens, the height direction of a specimen was parallel to the orientation of strands (i.e. the major direction).

The dimensions of the panel that was cut from the full-scale one as provided by Arbec company, as shown in Figure 2.11, would be 12’’ x 12’’ x 7/8’’ (305 x 305 x 22mm). Each 2 -layer 12 x 12” panel used 19g PF or Isocyanate resin. According to the ASTM D1037-12, a block shear specimen is fabricated as shown in Figure 2.3.3, the specimen will be from 1 to 2 in. (25 to 51 mm) thick, depending on the thickness of the panel. For the shear block test, preprocessed OSB with a 2-inch nominal height was used for the panels in this lab. The panels investigated were built up with 2 layers. Thus, a test specimen was 2 in. (51 mm) in length, 2 in. (51 mm) in width, and 7/8 in. (22mm) in depth. For the short span bending test, the specimens were also cut from the panel shown in Figure 2.12, and the specimen was 5.5 in. (140mm) in length, 1.5 in. (38mm) in width, 7/8 in. (22mm) in depth.

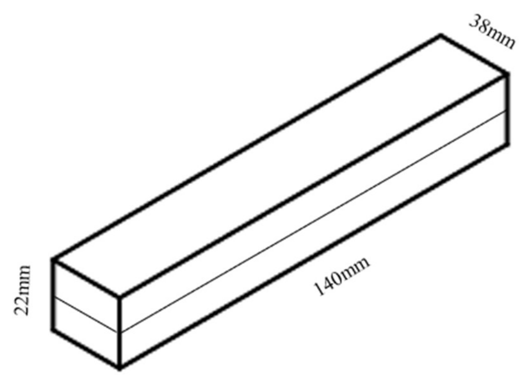
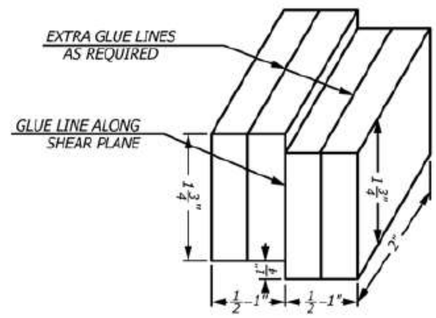


Figure 2.12 Sizes of specimen short-span bending test.



Metric Equivalents				
in.	¼	1	1¾	2
mm	6	25.4	44	51

Figure 2.13 Block Type Glue-line Test Specimen (Source: ASTM D1037)

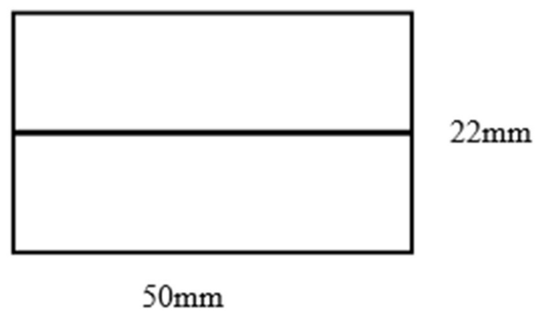


Figure 2.14 Sizes of specimens' width and depth for block shear test.

The dimensions of two types of specimens are shown in the Table 2.3.1:

Table 2.5 Dimensions of short-span bending and block shear specimens

	Depth/mm	Width/mm	Length/mm
Short span bending	22	38	140
Block shear	22	50	50

3 Methods

3.1 Short-span bending test

The short-span bending test is shown in Figure 3.3. The span was 121mm. The test setup used was center pointed. With reference to ASTM D1037 (ASTM International 2012), a span-to-depth ratio of 5 was used to evaluate horizontal shear strength. For each test, there was approximately 12mm (0.5 inch) of overhang beyond the end reaction supports. The test was run in the displacement control mode at a rate of 2 mm/min via the Mechanical Test System (NVLAP Lab code: 200301-0). The load, crosshead movement, LVDT, and elapsed time were recorded at a rate of 0.2Hz.

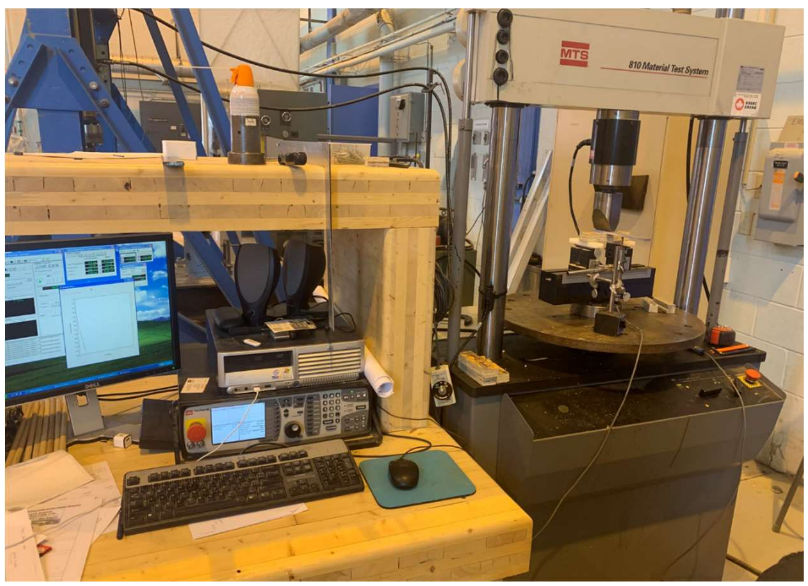


Figure 3.1 MTS testing machine.

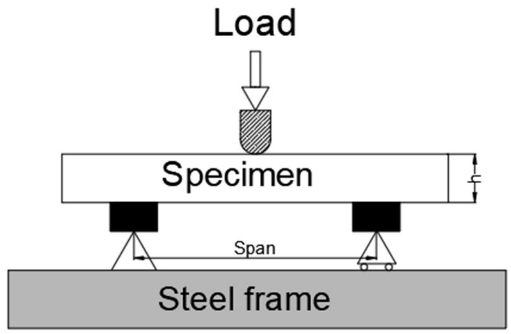


Figure 3.2 Short span bending set-up instruction

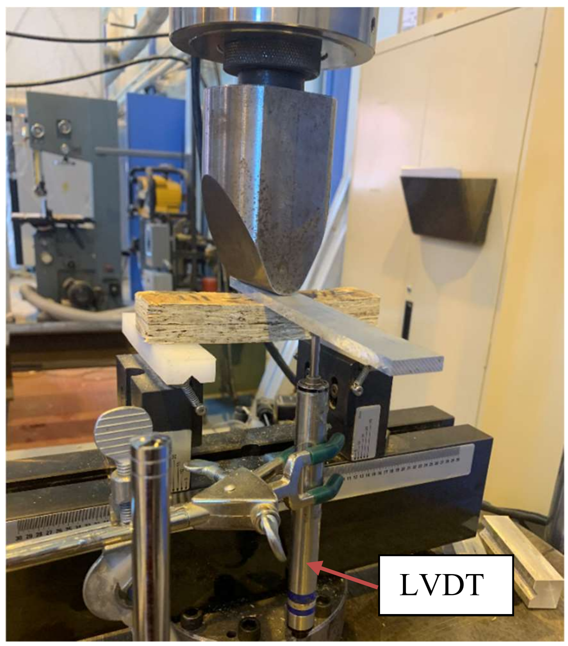


Figure 3.3 Short span bending set-up in the lab.

According to the ASTM D198, the maximum horizontal shear strength of a short span bending specimen can be calculated using Equation 3.1:

$$\tau_1 = \frac{3P_{max}}{4b_1d_1} \tag{3.1}$$

b_1 = width of the specimen, mm;

d_1 = depth of the specimen, mm;

P_{max} = maximum load, N; and

τ_1 = maximum horizontal shear strength, MPa.

3.2 Block shear test

The block shear test setup is shown in Figure 3.4 The test setup was block shear. As specified in ASTM D1037 (ASTM International 2012), squares that were a size of 50 x 50 x 22mm were used in the block shear test to evaluate shear strength. The load speed was 2 mm/min. The load, crosshead movement, LVDT, and elapsed time were recorded at a rate of 0.2Hz.

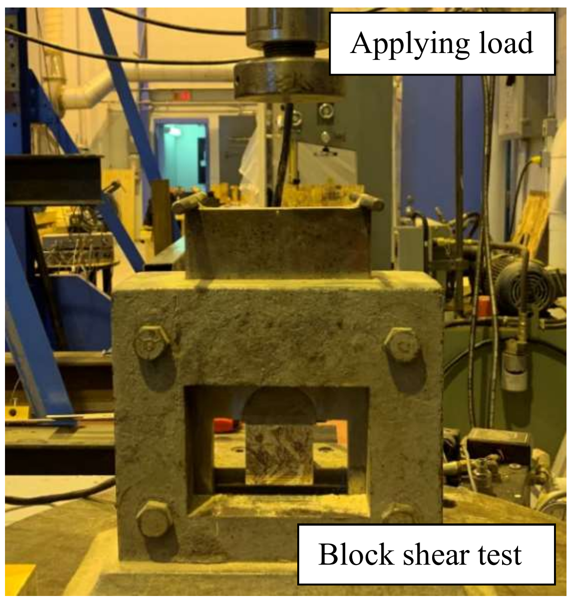


Figure 3.4 Machine set-up for block shear test.

According to the ASTM D1037, the maximum shear strength of a block shear specimen can be calculated in accordance with Equation 3.2:

$$\tau_2 = \frac{P_{max}}{b_2 d_2} \tag{3.2}$$

where:

b_2 = width of the shear area, mm;

d_2 = depth of the shear area, mm;

P_{max} = maximum load, N; and

τ_2 = maximum shear strength, MPa.

3.3 Wood Percentage failure

The percentage wood failure (PWF) of a block shear specimen was visually estimated by the author according to ASTM D 1037, which is defined as the ratio of the area of wood failure to the total area. It can be calculated using Equation 3.3:

$$PWF = \frac{A_{wood\,failure}}{A_{total}} \times 100\% \qquad (3.3)$$

Where,

PWF = the percentage wood failure of the specimens, %;

$A_{wood\ failure}$ = the area of the region where is wood failure; and

A_{total} = the total area of the failure surface of the specimens.

4 Results and Discussion

It was found that some data from the short-span bending tests and block shear tests were not reasonable, far away from the means. This could be due to the unproper manufacturing of specimens and operating errors during testing, in particular for block shear specimens and testing. The specimens should be bonded within 24h after applying surface treatments, however, the group that used isocyanate and was cut in the major direction was stored in the laboratory for almost 2 months. The surface activation would change during this time due to surface swelling caused by air exposure. The dusts in the air would also attach to the surfaces and influence the adhesive penetration. The OSB strands on the surfaces that were processed by treatments could also have been susceptible to oxidation. Thus, a preliminary treatment on data was applied, i.e. those data were removed when their values were beyond the boundaries of "Mean + Standard deviation" and "Mean - Standard deviation". This means the outliers of each group of data at a given test condition were culled in the data analysis. The summarized results of this data selection method were shown in Table 4.1 and Table 4.2.

Table 4.1 Summarize of data selection in short-span bending test

Adhesive	Direction	Treatment	Number of data removed	Number of data used	Total
PF	Major	None	6	10	16
		100 Sanding	4	12	16
		600 Sanding	6	10	16
		Tooth-plate	5	11	16
		100 Sanding & Tooth-plate	4	12	16
		600 Sanding & Tooth-plate	6	10	16
	Minor	None	3	13	16
		100 Sanding	5	11	16
		600 Sanding	6	10	16
		Tooth-plate	7	9	16
		100 Sanding & Tooth-plate	4	12	16
		600 Sanding & Tooth-plate	3	13	16
ISO	Major	None	6	10	16
		100 Sanding	4	12	16
		600 Sanding	5	11	16
		Tooth-plate	6	10	16
		100 Sanding & Tooth-plate	4	12	16
		600 Sanding & Tooth-plate	6	10	16
	Minor	None	7	9	16
		100 Sanding	6	10	16
		600 Sanding	5	11	16
		Tooth-plate	3	13	16
		100 Sanding & Tooth-plate	5	11	16
		600 Sanding & Tooth-plate	6	10	16

Table 4.2 Summarize of data selection in block shear test

Adhesive	Direction	Treatment	Number of data removed	Number of data used	Total
PF	Major	None	7	9	16
		100 Sanding	5	11	16
		600 Sanding	6	10	16
		Tooth-plate	5	11	16
		100 Sanding & Tooth-plate	6	10	16
		600 Sanding & Tooth-plate	3	13	16
	Minor	None	6	10	16
		100 Sanding	4	12	16
		600 Sanding	4	12	16
		Tooth-plate	4	12	16
		100 Sanding & Tooth-plate	7	9	16
		600 Sanding & Tooth-plate	3	13	16
ISO	Major	None	8	8	16
		100 Sanding	8	8	16
		600 Sanding	7	9	16
		Tooth-plate	6	10	16
		100 Sanding & Tooth-plate	5	11	16
		600 Sanding & Tooth-plate	7	9	16
	Minor	None	5	11	16
		100 Sanding	5	11	16
		600 Sanding	6	10	16
		Tooth-plate	6	10	16
		100 Sanding & Tooth-plate	4	12	16
		600 Sanding & Tooth-plate	5	11	16

4.1.1 Short-span bending tests

All the short-span bending specimens were divided into 24 sets in terms of three factors, panel direction (the major direction and minor direction), surface treatment (six surface treatments provided in Chapter 2.2), and adhesive (PF resin and Isocyanate resin). The raw data of short-span bending test was shown in Appendix 1. The quality of some laminated OSB specimens seemed to be not as good as expected, resulting in unexpected strength. For example, the group using PF and tooth-plate in the minor direction had 7 data points deleted and the group using Isocyanate and no treatment in the minor direction also had 7 data points deleted. A Minitab ANOVA General Linear Model was used to analyze the relation between the three factors and the horizontal shear strength. Adhesive, surface treatment, and panel direction were chosen to be fixed effects. The horizontal shear strength calculated from the short-span bending tests was used as the response. The detailed results are given in Appendixes 1 and 5. Figures 4.1 and Table 4.4 provide a summary of the horizontal shear strength values in different comparisons.

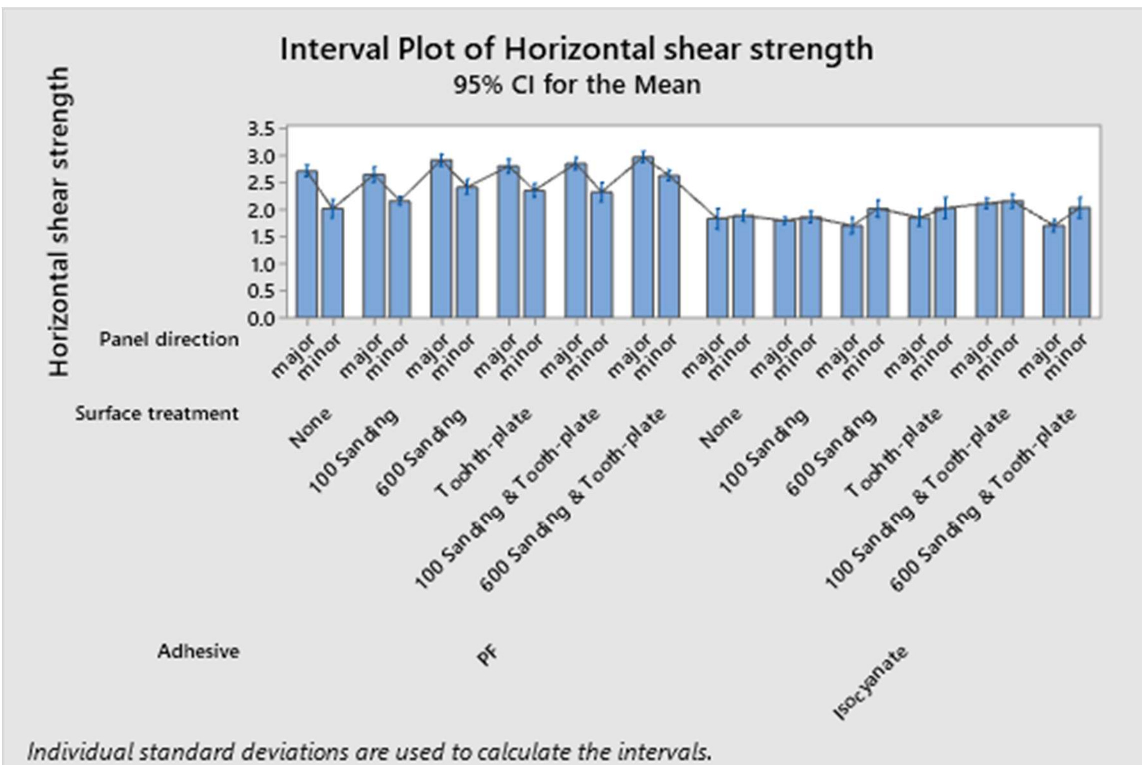


Figure 4.1 Horizontal shear strength about different surface treatment groups in major and minor direction

Table 4.3 Results of short-span bending test run by Minitab

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Adhesive	1	27.060	27.0600	346.46	0.000
Surface treatment	5	2.898	0.5796	7.42	0.000
Panel direction	1	1.953	1.9525	25.00	0.000
Error	253	19.760	0.0781		
Lack-of-Fit	16	9.937	0.6211	14.99	0.000
Pure Error	237	9.823	0.0414		
Total	260	51.182			

Based on the results that were run by Minitab in Appendix 9 and Table 4.3, the p-value of all three factors were much smaller than 0.05, at a 95% confidence interval. This suggests that the horizontal shear strength was significantly affected by the panel direction, surface treatment, and type of adhesive. "Lack of fit" can occur if several, unusually large residuals result from fitting the model. The sum of squares for pure error is the sum of the squared deviations of the responses from the mean response in each set of replicates. Pure error was not be used for the data analysis in this project. According to the Figure 4.1, the average shear strength of those that used PF was larger than those that used isocyanate in the major direction during manufacturing. The average shear strength values of all sets of specimens tested in the major direction were about 10-30% larger than those in the minor direction because the wood had unique and independent properties in different direction, while OSB was also made in orientation. The largest horizontal shear strength was 3.16MPa, which appeared in the group that used PF, 600 mesh sanding, and metal tooth-plate in the major direction. The average horizontal shear strength value was 2.25MPa.

The surface treatment type could have a clear influence among different groups when the adhesive options remained the same.

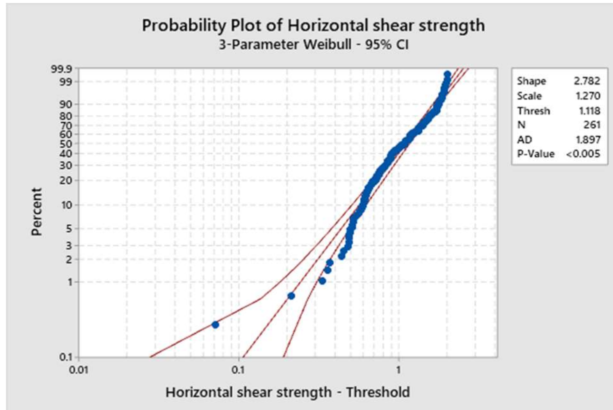
Figure 4.1 shows that PF acted as a stronger adhesive than Isocyanate in a short span bending test, as well as the combination of no surface treatment and Isocyanate may cause lower shear strength in laminated OSB product manufacturing process if the specimens chosen were used in this surface process method.

Table 4.4 Horizontal shear strength in two different panel positions

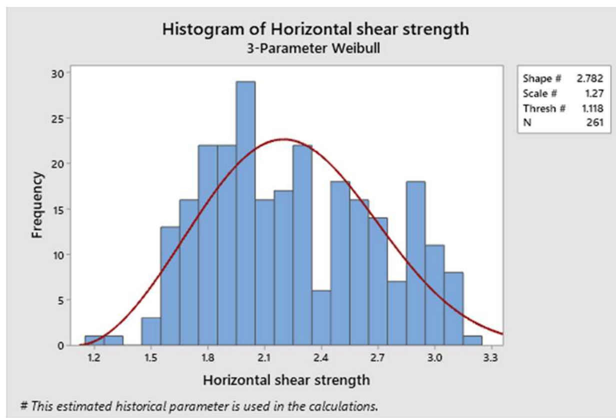
Adhesive	Position	Surface treatment	Horizontal shear strength/ (MPa)
PF	Center	None	2.03
		100 Sanding	2.11
		600 Sanding	2.48
		Tooth-plate	3.02
		100 Sanding & Tooth-plate	3.42
		600 Sanding & Tooth-plate	3.44
	Edge	None	1.99
		100 Sanding	1.99
		600 Sanding	2.06
		Tooth-plate	2.56
		100 Sanding & Tooth-plate	2.88
		600 Sanding & Tooth-plate	3.31
ISO	Center	None	1.95
		100 Sanding	1.98
		600 Sanding	2.00
		Tooth-plate	1.87
		100 Sanding & Tooth-plate	2.02
		600 Sanding & Tooth-plate	2.03
	Edge	None	1.87
		100 Sanding	1.95
		600 Sanding	1.93
		Tooth-plate	1.74
		100 Sanding & Tooth-plate	2.00
		600 Sanding & Tooth-plate	1.99

As discussed in Chapter 2, eight short-span bending specimens were cut from two different locations of a panel, i.e. center and edge, see Figure 2.11. As shown in Table 4.4, most of horizontal shear strength values of the "Center" specimens were larger those of "Edge" ones. The average shear strength of "Center" specimens was about 4-8% larger than the "Edge" ones.

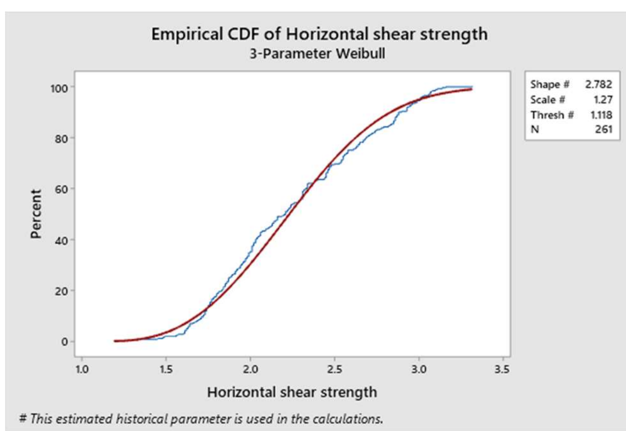
The adhesion of the glue depends on the wood-glue bonding chain. Adhesive bonding performance between wood elements is presumed to be significantly influenced by the degree of penetration of adhesive into the porous network of interconnected cells (Onur, 2016). The central surface would have a more uniform structure than the edge of the surface for bonding formation. As for the hot-pressing procedure, the top and bottom surfaces of the specimen would reach the platen temperature virtually instantly, meanwhile the bond line would remain at room temperature towards the beginning of heat and pressure applications. The energy at the edges of the specimen could be lost when the water is released, while the core part of specimen could have a higher MC (Arun Gupta et al, 2013). The edge of the specimen might be over cured when the central position is fully cured. So, the adhesive could have a more uniform dispersion pattern due to the fact that it was applied at the center of a panel before pressing and could show a stronger shear strength.



(a)



(b)



(c)

Figure 4.2 Three-parameter Weibull of horizontal shear strength

Weibull distribution was found to best describe the results, i.e. the range and dispersibility of horizontal shear strength. The Shape, Scale, and Thresh of Weibull were determined by the probability plot shown in Figure 4.2 (a). According to 3-parameter Weibull results, there would be 30-80% likelihood to predict the range of best fit for the horizontal shear strength of laminated OSB specimens with a Weibull distribution of 1.8-2.4MPa.

In a brief summary, the three factors would affect the horizontal shear strength at a 95% confidence level. Using PF, 600 mesh sanding paper, and metal tooth-plate could provide a stronger horizontal shear strength for laminated OSB specimens. Specimens chosen from the central position or chosen to be cut in the major direction would have larger horizontal shear strength. The range of horizontal shear strength could fit into that of plywood sheathing products (Ross, 2010).

4.1.1 Block shear tests

All the block shear specimens were divided into 24 sets in terms of three factors, panel direction (the major direction and minor direction), surface treatment (six surface treatments provided in Chapter 2.2), and adhesive (PF resin and Isocyanate resin). The raw data from the block shear test was shown in Appendix 2. The quality of some LOSB specimens seemed to be not as good as expected, resulting in unexpected shear strength. For example, there were 8 data points removed from the group that used isocyanate resin and no surface treatment in the major direction and the same number of data points were removed from the group that used isocyanate and applied no treatment in the major direction. A Minitab ANOVA General Linear Model was used to analyze the relationship between the three factors and one response (i.e. shear strength). Adhesive, surface treatment, and panel direction were chosen to be fixed effects. The detailed results are given in Appendixes 2 and 6. Figures 4.3 and Table 4.6 provide a summary of the shear strength values in different comparisons.

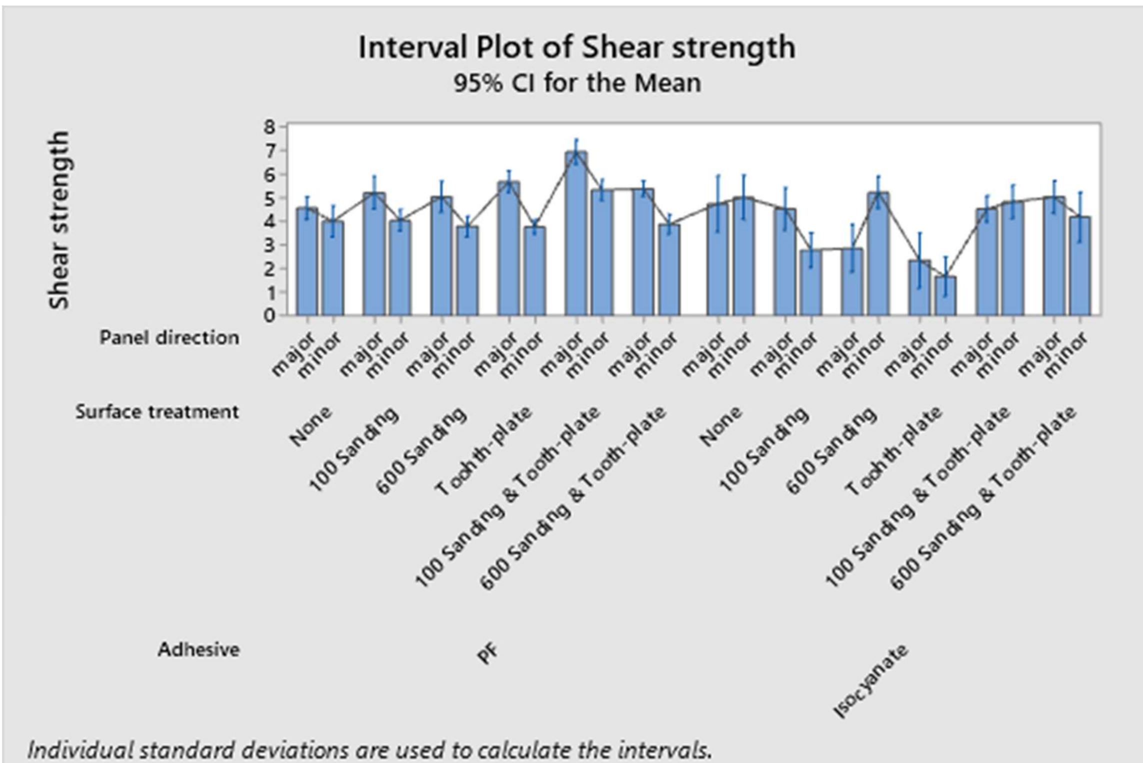


Figure 4.3 Shear strength about different surface treatment groups in major and minor direction

Table 4.5 Results of block shear test run by Minitab

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Adhesive	1	42.47	42.4656	27.68	0.000
Surface treatment	5	89.60	17.9200	11.68	0.000
Panel direction	1	32.65	32.6498	21.28	0.000
Error	242	371.32	1.5344		
Lack-of-Fit	16	153.45	9.5909	9.95	0.000
Pure Error	226	217.86	0.9640		
Total	249	534.48			

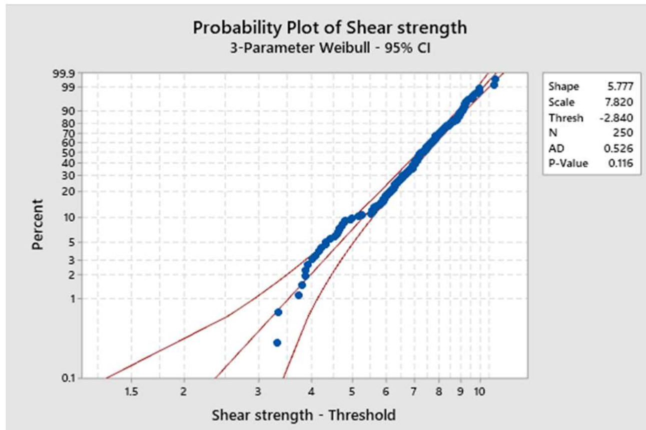
Based on the results that were run by Minitab in Appendix 6 and Table 4.5, the p-value of all three factors were much smaller than 0.05, at the 95% confidence interval. This suggests that shear strength was significantly affected by the panel direction, surface treatment, and type of adhesive. According to Figure 4.3, the average shear strength of PF use was larger than that of Isocyanate use, both being in the same direction during manufacturing. The average shear strength values of all sets of specimens tested in the major direction were about 5-40% larger than those in the minor direction when PF was used for bonding material. The largest shear strength was 8.02MPa, which appeared in the group that used PF, 100 mesh sanding, and metal tooth-plate in the major direction. The smallest shear strength was 0.48MPa which appeared in the group that used Isocyanate and tooth-plate in the minor direction. The average shear strength value was 4.4MPa. The type of surface treatment can demonstrate a clear influence among different groups when the adhesive choices remain the same.

Figure 4.3 also provides the same result as the short-span bending test, demonstrating that PF acted as a stronger adhesive than Isocyanate based on the shear strength data; the combination using tooth-plate surface treatment and Isocyanate may cause lower shear strength in the laminated OSB product manufacturing process if the chosen specimens used this surface process method.

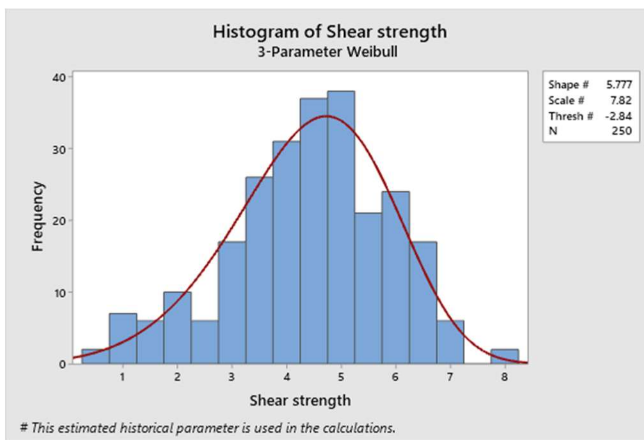
Table 4.6 Shear strength in two different panel positions

Adhesive	Position	Surface treatment	Horizontal shear strength/ (MPa)
PF	Center	None	4.32
		100 Sanding	5.21
		600 Sanding	8.07
		Tooth-plate	5.53
		100 Sanding & Tooth-plate	7.06
		600 Sanding & Tooth-plate	5.68
	Edge	None	4.01
		100 Sanding	4.77
		600 Sanding	6.12
		Tooth-plate	5.3
		100 Sanding & Tooth-plate	6.35
		600 Sanding & Tooth-plate	4.33
ISO	Center	None	3.89
		100 Sanding	4.21
		600 Sanding	4.55
		Tooth-plate	3.44
		100 Sanding & Tooth-plate	4.03
		600 Sanding & Tooth-plate	4.16
	Edge	None	3.46
		100 Sanding	3.74
		600 Sanding	4.05
		Tooth-plate	3.41
		100 Sanding & Tooth-plate	4.03
		600 Sanding & Tooth-plate	4.11

As discussed in Chapter 2, eight block shear specimens were cut from two different locations of a panel, i.e. center and edge, see Figure 2.11. As shown in Table 4.6, most of the strength values for the "Center" specimens were larger the "Edge" ones. The average shear strength of "Center" specimens was about 3-10% larger than the "Edge" ones.



(a)



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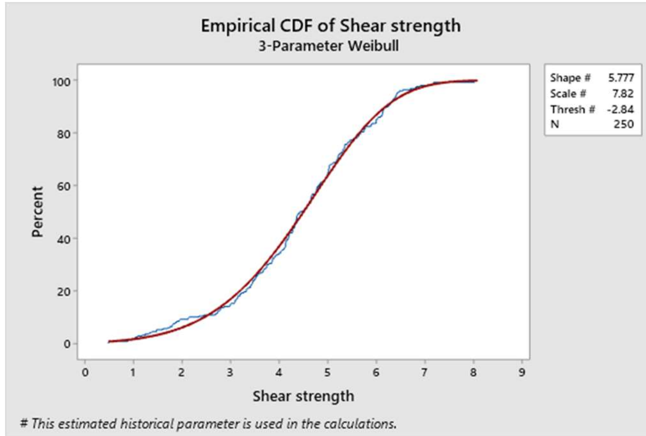

(c)

Figure 4.4 Three-parameter Weibull of shear strength

Based on the instruction of MINITAB, weibull distribution was found to best describe the results, i.e. the range and dispersibility of shear strength. The Shape, Scale, and Thresh of Weibull were determined by the probability plot shown in Figure 4.4 (a). According to 3-parameter Weibull results, there would be 30-80% likelihood to predict the range for the best fit of LOSB specimens' horizontal shear strength with a Weibull distribution between 3.5-6.5MPa. In comparison with the plywood products, their shear strength value was in the range of 5.5-6.9MPa (Ross, 2010) which was close to the shear strength of LOSB specimens. These results provide an acceptable strength for making LOSB products to replace parts of the plywood products in terms of load-carrying capacity. To compare with the plywood sheathing products which had less than 5 layers, the glue-line shear strength was in a range of 2.9-7.0MPa (APA, 2013) which was similar to the block shear strength of laminated OSB specimens. The results showed that laminated OSB products could be used to replace part of plywood products in terms of load-carrying capacities.

In a brief summary, all three factors statistically significantly affected shear strength. Using PF, 100 mesh sanding paper, and metal tooth-plate could provide a stronger shear strenth for LOSB specimens. Specimens chosen from the central position or cut in the major direction would have better shear strength performance. The range of shear strength could fit within that of plywood products.

4.1.2 Percentage Wood Failure

According to ASTM D1037, the PWF of a block shear specimen was estimated by the equation shown in Section 3.3. and the results are shown in Appendixes 3 and 4. After breaking a block shear specimen, the image of a specimen that had a glue-line failure mode was shown in Figure 4.5. More than 50% of the failure happened in the glue-line part. The failure of breaking in the wood is also shown in Figure 4.6. Figure 4.6 (a) illustrates a failure along the glue-line while the wood failure shown by Figure 4.6 (b).

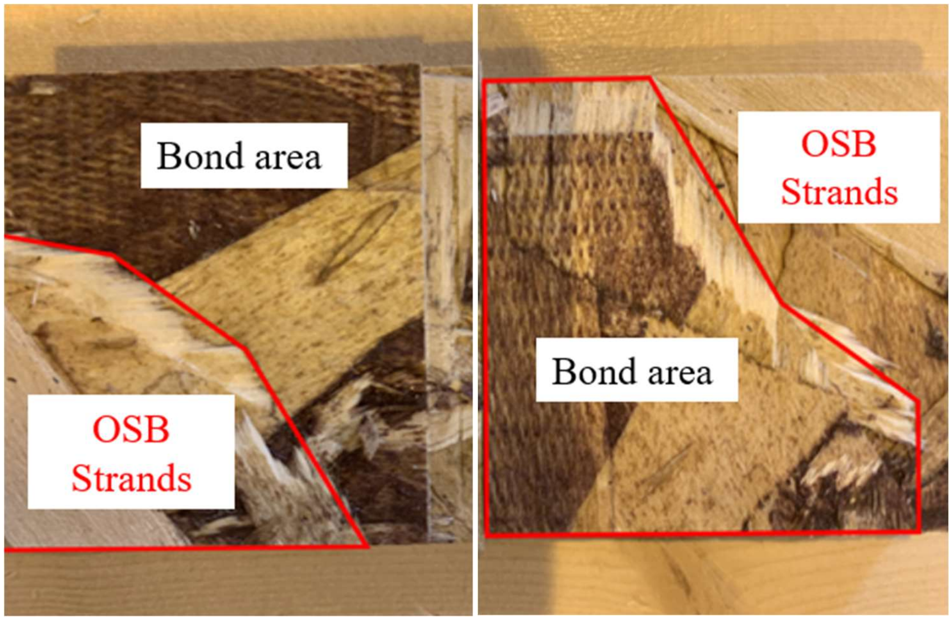

Figure 4.5 Example image showing the failure on two faces along the bond-line of a block shear specimen

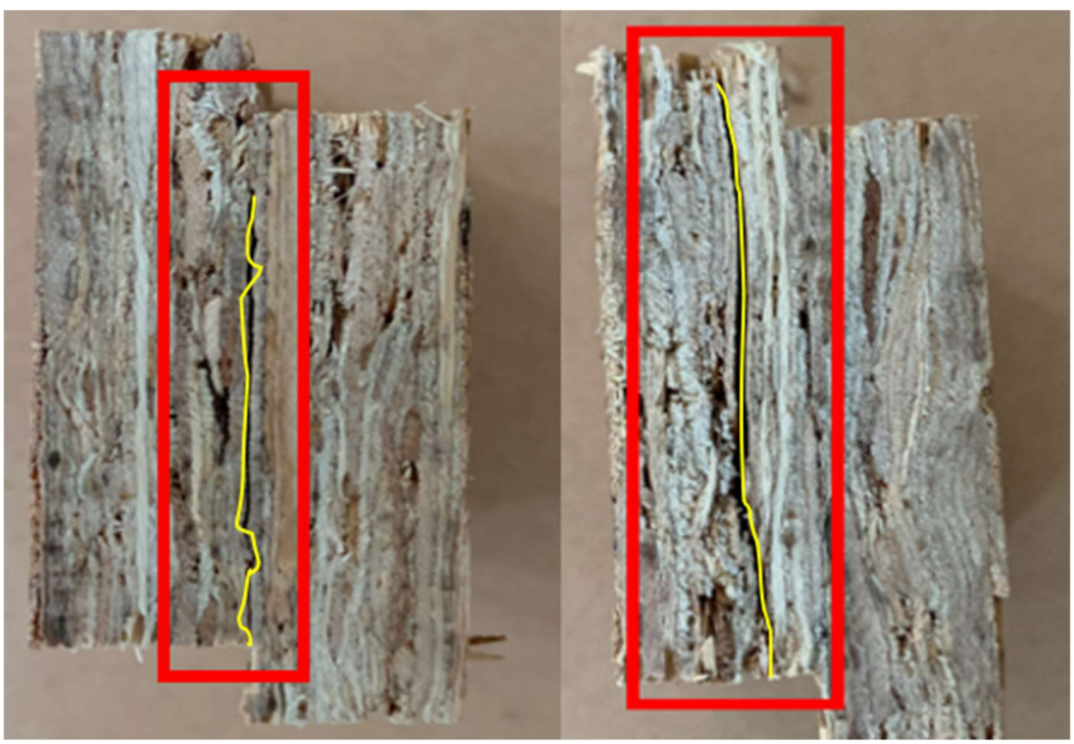

Figure 4.6 The example images for failure mode (Taken from the side of block)

Table 4.7 Summary of PWF in block shear test

Adhesive	direction	glue-line dominant	Wood failure dominant			Total
		WF<50%	80-89%	90-99%	100%	
PF	Major	3	5	9	47	64
	Minor	1	4	11	52	68
ISO	Major	6	4	5	40	55
	Minor	3	5	12	45	65
Summary		13	18	37	184	252

From Table 4.7, it can be found that 95% of the block shear specimens had a percentage wood failure of 80% and above, suggesting that the internal strength of OSB specimens was smaller than the bond-line strength. In addition, only four specimens failed along the bond-line of the specimens tested with the use of PF to bond the specimens. However, there were 9 blocks bonded with isocyanate that failed in the bond-line part and 6 of the failed specimens were from the "isocyanate" group in the major direction faltered due to surface inactivation caused by the delay of grouping and pressing. Overall, the bonding quality was very good when the applied manufacturing paragraphs were used in this study.

4.1.3 Bond quality comparison among different surface treatment

Based on the results of short-span bending test, block shear test and evaluation of PWF, two surface treatment method shew a good bond quality. The bond strengths between group "Using sanding paper" and "Using sanding paper and metal tooth-plate" were compared due to the consideration of manufacturing cost. Table 4.8 provided the results.

Table 4.8 Comparison between two surface treatments

Direction	Group	Horizontal shear strength/MPa	Block shear strength/MPa	Number of failed in bond-line
major	PS1	2.65	5.23	1
	PS6	2.92	5.05	1
	PTS1	2.86	6.95	0
	PTS6	2.98	5.40	1
	IS1	1.80	4.54	1
	IS6	1.70	2.87	1
	ITS1	2.12	4.54	1
	ITS6	1.71	5.04	2
minor	PS1	2.17	4.06	0
	PS6	2.42	3.79	1
	PTS1	2.33	5.34	0
	PTS6	2.64	3.89	0
	IS1	1.87	2.79	2
	IS6	2.02	5.25	0
	ITS1	2.16	4.85	1
	ITS6	2.04	4.20	1

According to the results of Table 4.8 provided, the group which chose to using sanding paper rather than using sanding paper and tooth-plate would have 5-8% and 17-23% lower horizontal shear strength and block shear strength than the group that used sanding paper and tooth-plate at the same time, respectively, while the adhesive and panel direction were determined. Thus, the best bonding performance would appear in the group of using sanding paper and metal tooth-plate. Most of the bending specimens failed in the OSB rather than the bonding part, that's why this orange line shows a smooth trend. Though the trend of blue line is not stable, the range of horizontal shear strength was smaller than the range of block shear strength, this result could show that most of the glue-line parts were stronger than the OSB specimens. For the orange line, there was no significant difference among the three largest horizontal shear strength group, while the group which used PF + 100 Sanding + Tooth-plate provided the largest block shear strength.

4.1.4 Relation between horizontal shear strength and block shear strength

Failure will occur along the bond line of an adhesively bonded specimen under short-span bending, when the horizontal shear strength exceeds the shear strength of a bond line. Most of the specimens failed in the wooden part rather than in the glue-line during the short-span bending test, Figure 4.7 provides an example of failure in the bending test.

Figure 4.7 Failure in strands rather than along the bond line.

Table 4.9 Average of horizontal shear strength and shear strength

Adhesive	Direction	Horizontal shear strength/ (MPa)	Block shear strength/ (MPa)
PF	major	2.82	5.49
	minor	2.32	4.09
ISO	major	1.84	3.98
	minor	2.01	3.98
	Position	Horizontal shear strength/ (MPa)	Block shear strength (MPa)
PF	Center	2.75	5.98
	Edged	2.47	5.15
ISO	Center	1.98	4.05
	Edged	1.91	3.80

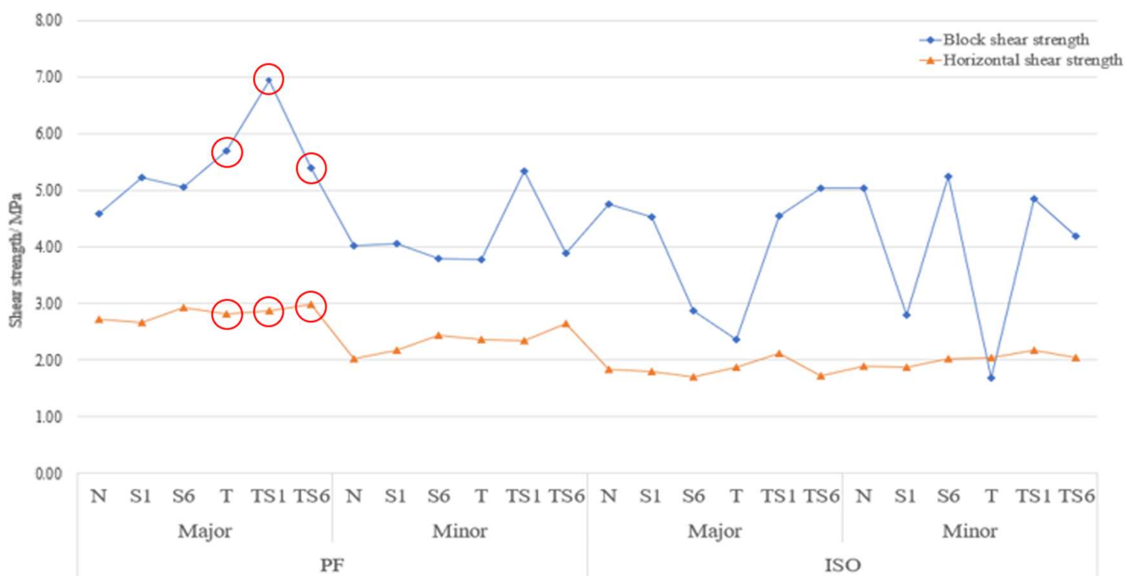

Figure 4.8 Average shear strength of two tests.

The average horizontal shear strength of LOSB bending specimens was calculated to be 3.16 MPa by Eq. (1) and the average shear strength of block shear LOSB specimens was

4.4MPa, calculated by Eq. (2). This indicates that the maximum horizontal shear strength was 28% lower than that of the block shear strength (Figure 4.8), which could be due to the weakest bond area detected under short-span bending. As Table 4.8 shows, the range of horizontal shear strength was smaller than the range of block shear strength, this result could show that most of the glue-line parts were stronger than the OSB specimens. This is an advantage over the block shear test that only provides an average shear strength value over a bonding area (Gong et al. 2019). 24 average sets of data were used to draw the regression line.

5. Conclusions and future work

5.1 Conclusions

A modified center-point short-span bending test method and block shear test have been proposed to evaluate the bond quality of LOSB panels, that were bonded using two different type of adhesive (PF & ISO). Shear strength, shear strength, and PWF results were compared with those of the tested specimens and the following conclusions can be drawn:

1) According to the results from short span bending and block shear tests, the best surface process could be the combination of PF resin, sanding paper, and tooth-plate with determined hot-pressing parameters according to the results of short span bending, block shear test, and PEF. PF acted as a stronger adhesive than Isocyanate during the tests. One of the testing groups, “PTS1”, showed a maximum shear strength (8.02MPa).

2) Based on the pre-lab to determine the hot-pressing parameters in Chapter 2.2.1, the OSB product was not fully cured when the pressing time and temperature were 10.5min and 120 °C. If the curing time and temperature were changed to 20.5min and 170 °C, the product would be over cured. The final hot-pressing parameters (pressing time & pressing temperature & pressure) for this project should be 15min, 150°C, and 100psi (0.69MPa).

3) The specimens cut in the major direction would have a 20-40% higher bond quality than those in the minor direction. The average shear strength of "Center" specimens in this bending test was about 4-8% larger than the "Edge" specimens in the short span bending test. The average shear strength of "Center" specimens in the block shear test was about 3-10% larger than the "Edge" specimens. Clearly, the central bond line of the laminated OSB specimens made in this project was stronger than the edged bond strength.

4) There will be 95% confidence interval for us to propose that the horizontal shear strength value would be affected by the panel direction, surface treatment, and type of adhesive. The average horizontal shear strength value was 2.25MPa in this project. There will be 95% confidence interval for us to say that the shear strength value would be affected by the same three factors based on the results calculated by Minitab, and the average of shear strength value was 4.4MPa.

5) The delay of grouping and pressing after surface processes were done would have an impact on bond quality. The short-span bending test had an advantage over the block shear test, which only provided an average shear strength over

a bonding area.

6) The average bond line of the Shear strength of PF or Isocyanate bonded OSB specimens were larger or less than that of the OSB material itself, respectively, at a given strength direction based on the evaluation of PWF. These methods can be accepted. The surface processing methods proposed in this study improved the practicability of thicker OSB products manufacturing.
7) The recommendation of surface treatment method would be using sanding and metal tooth-plate indenting to improve the bond quality of LOSB specimens.

5.2 Future work

This project was focused on the investigation of how surface treatment impacted the bond quality of 2-layer laminated OSB specimens. The following future work will be recommended:

1) To identify another structural adhesive to make laminated OSB lumber products that could be cured without hot-pressing. The phenol-resorcinol-formaldehyde adhesive could be a good candidate since it can be pressed and cured at room temperature and with longer pressing time and higher pressure than PF and Isocyanate;
2) To examine the bond quality between smooth and rough faces of OSB; and
3) To fabricate full size laminated OSB lumber products and examine their mechanical properties. These products can be used in construction such as short beams and wall studs.

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Appendixes

Appendix 1.1 Summary of horizontal shear strength

			Panel 1				Panel 2			
Adhesive	Direction	Treatment	S1	S2	S3	S4	S1	S2	S3	S4
PF	Major		2.69	2.54	3.28	2.9	2.61	3.11	2.38	2.78
		100 Sanding	2.46	2.35	2.55	2.47	2.38	2.96	2.48	2.87
		600 Sanding	3.21		3.1	2.94	2.56	2.61	2.74	3.06
		Tooth-plate	2.58	2.96	2.99	2.73	2.64	2.21	2.84	3.15
		100 Sanding & Tooth-plate	3.62	2.15	3.06	2.67	3.02	2.53	3.22	2.45
		600 Sanding & Tooth-plate	2.93	3.08	2.83	3.42	2.32	2.74	3.07	2.21
	Minor	None	2.09	1.4	2.31	2.01	2.28	2.15	1.83	1.71
		100 Sanding	2.31	2.16	2.03	2.32	2.14	1.76	2	2.03
		600 Sanding	2.45	1.98	2.63	2.55	2.3	2.02	1.86	2.45
		Tooth-plate	1.97	1.94	2.06	2.44	2.34	2.55	2.31	2.78
		100 Sanding & Tooth-plate	2.4	1.96	2.74	2.57	2.04	1.4	1.79	2.16
		600 Sanding & Tooth-plate	2.62	2.82	2.47	2.47	3.04	1.9	2.48	

Appendix 1.2 Summary of horizontal shear strength

			Panel 1				Panel 2			
Adhesive	Direction	Treatment	S1	S2	S3	S4	S1	S2	S3	S4
ISO	Major	None	1.62	1.63	1.99	2.07	1.45	1.62	1.23	1.76
		100 Sanding	1.84	1.89	2.01	1.8	2.2	1.53	1.91	1.5
		600 Sanding	1.61	1.75	1.84	1.92	2.2	2.22	2.01	1.49
		Tooth-plate	1.8	1.93	1.43	1.6	1.48	1.15	1.34	1.79
		100 Sanding & Tooth-plate	1.55	1.84	1.56	1.42	2.21	2.13	2.31	2.43
		600 Sanding & Tooth-plate	1.61	1.61	1.56	1.46	1.57	2.15	1.77	
	Minor	None	1.65	1.72	1.89	1.86	1.87	1.61	1.68	1.74
		100 Sanding	1.91		2.3	2.5	2.34	1.53	1.72	2.05
		600 Sanding	1.95	2.25	2.23	2.46	1.73	2.28	2.06	2.38
		Tooth-plate	1.44	1.87	1.69	1.88	1.81	1.91	1.8	1.73
		100 Sanding & Tooth-plate	3.08	2.5	1.44	1.53	1.27	2.34	1.92	2.22
		600 Sanding & Tooth-plate	2.47	1.75	1.41	1.46	2.21	1.27	1.76	2.04

Appendix 1.3 Summary of horizontal shear strength

			Panel 3				Panel 4			
Adhesive	Direction	Treatment	S1	S2	S3	S4	S1	S2	S3	S4
PF	Major	None	2.69	2.45	3.01	2.54	3.13	2.75	3.33	2.68
		100 Sanding	2.88	2.54	3.11	2.93	3.2	2.45	2.86	3.33
		600 Sanding	2.67	2.77	3.11	2.95	2.48	3.13	2.98	2.87
		Tooth-plate	2.07	2.2	3.16	3.07	2.86	2.44	2.86	2.93
		100 Sanding & Tooth-plate	2.86	2.64	2.79	2.85	3.01	2.85	2.99	3.03
		600 Sanding & Tooth-plate	3.01	2.93	3.42	2.88	3.14	3.16	2.48	3.33
	Minor	None	1.33	1.94	2.01	2.13	2.11	2.34	2.51	2.45
		100 Sanding	1.93	2.06	2.22	2.41	2.45	2.31	1.88	2.24
		600 Sanding	1.79	2.34	2.65	2.84	1.97	2.3	2.55	2.71
		Tooth-plate	2.21	2.06	2.74	2.56	2.45	2.31	2.81	2.9
		100 Sanding & Tooth-plate	2.06	2.31	2.58	2.63	1.98	2.58	2.75	2.68
		600 Sanding & Tooth-plate	2.85	2.45	2.88	2.56	2.97	2.65	2.71	2.7

Appendix 1.4 Summary of horizontal shear strength

			Panel 3				Panel 4			
Adhesive	Direction	Treatment	S1	S2	S3	S4	S1	S2	S3	S4
ISO	Major	None	1.99	1.08	2.33	1.87	2.69	2.42	2.42	2.53
		100 Sanding	1.63	1.7	1.78	1.77	1.96	1.67	1.85	1.77
		600 Sanding	1.74	1.18	1.83	1.1	1.19	2.29	1.73	1.64
		Tooth-plate	1.99	2.2	1.74	2.09	1.95	2.43	2.53	2.64
		100 Sanding & Tooth-plate	1.97	2.29	2.19	2.24	1.94	2.02	2.13	2.16
		600 Sanding & Tooth-plate	1.64	2.03	2.08	1.3	1.71	1.66	2.36	1.9
	Minor	None	2.16	2.26	2.51	1.99	1.87	2.24	1.94	2.26
		100 Sanding	1.75	1.81	1.55	1.68	1.86	1.78	2.01	2.1
		600 Sanding	1.65	1.67	1.85	2.03	1.73	2.12	1.45	1.85
		Tooth-plate	2.72	2.32	2.46	2.61	1.76	2.14	2.31	2.79
		100 Sanding & Tooth-plate	2.01	1.97	2.26	2.61	2.01	1.98	2.34	2.24
		600 Sanding & Tooth-plate	2.02	2.23	2.39	1.64	2.46	2.44	2.38	1.97

Appendix 2.1 Summary of block shear strength

			Panel 1				Panel 2			
Adhesive	Direction	Treatment	S1	S2	S3	S4	S1	S2	S3	S4
PF	Major	None	3.49	3.22	6.65	4.5	4.13	7.97	4.97	7.72
		100 Sanding	4.53	5.02	6.03	3.85	4.18	3.33	6.42	7.69
		600 Sanding	6	6.28		7.15	3.34	4.77	5.23	6.15
		Tooth-plate	4.19	4.36	5.65	7.63	5.02	4.68	6.15	6.33
		100 Sanding & Tooth-plate	4.97	6.91	9.81	8.85	6.48	7.07	8.08	5.17
		600 Sanding & Tooth-plate	5.51	5.3	5.61	6.09	4.34	4.96	4.81	1.67
	Minor	None	2.74	2.39	5.21	5.74			5.25	5.19
		100 Sanding	2.34	3.41	4.65	4.38	3.47	3.22	4.13	3.52
		600 Sanding	3.14	2.78	3.86	4.33	3.44	2.19	4.58	4.65
		Tooth-plate	4.13	3.09	4.11	3.65	4.3	3.08	5.12	4.2
		100 Sanding & Tooth-plate	4.27	5.61	4.78	5.91	4.18		5.89	6.64
		600 Sanding & Tooth-plate	2.68	2.72	4.38	0.02	3.67	1.79	4.89	4.04

Appendix 2.2 Summary of block shear strength

			Panel 1				Panel 2			
Adhesive	Direction	Treatment	S1	S2	S3	S4	S1	S2	S3	S4
ISO	Major	None	0.4	0.2	8.71	6.29	5.21	6	4	
		100 Sanding	0.83		6.65	4.77	5.03	5.09	1.35	0.93
		600 Sanding	1.75	1.37	2.79	0.21	6.77	0.76	5.55	
		Tooth-plate	1.82		1.24	1.86	0.76	1.02	1.08	1.89
		100 Sanding & Tooth-plate	1.6	4.09	3.09	2.13	4.28	4.92	4.75	5.35
		600 Sanding & Tooth-plate	4.6	6.95	3.27	1.7	4.28	5.64	5	2.63
	Minor	None	5.2	4.27	3.69	2.99	1.24	1.38	3.19	
		100 Sanding	7.27	4.54	3.52		1.6		1.8	3.19
		600 Sanding	6.43	6.38	4.67	4.33	5.89	7.38	6.83	6.04
		Tooth-plate	0.28		0.89	1.79	1.03	0.49	1.18	1.7
		100 Sanding & Tooth-plate	2.16	2.04	3.49	3.32	4.58	7.25	4.93	7.09
		600 Sanding & Tooth-plate			6.29	2.98	2.73	1.65	3.37	3.32

Appendix 2.3 Summary of block shear strength

			Panel 3				Panel 4			
Adhesive	Direction	Treatment	S1	S2	S3	S4	S1	S2	S3	S4
PF	Major	None	3.74	4.83	5.76	3.36	5.02	4.14	6.68	4.13
		100 Sanding	6.45	6.82	7.39	8.03	4.33	3.94	5.31	4.6
		600 Sanding	0.87	3.56	7.21	5.31	4.14	4.35	4.75	6.86
		Tooth-plate	5.41	6.25	6.41	6.66	3.46	4.65	5.75	6.34
		100 Sanding & Tooth-plate	5.77	5.34	7.18	8.02	4.77	6.31	7.15	6.55
		600 Sanding & Tooth-plate	5.35	5.12	6.16	5.75	6.12	5.03	8.21	7.1
	Minor	None	2.79	3.74	4.96	4.12	3.45	1.02	4.36	3.55
		100 Sanding	1.03	3.11	5.04	4.19	6.23	4.36	5.22	5.43
		600 Sanding	4.21	1.45	3.6	5.58	2.86	3.42	4.65	5.03
		Tooth-plate	3.67	3.41	3.75	5.34		2.09	3.51	4.47
		100 Sanding & Tooth-plate	4.98	4.77	5.34	6.13	4.65	3.99	6.32	6.34
		600 Sanding & Tooth-plate	3.15	4.32	3.86	4.03	5.16	3.85	4.66	4.32

Appendix 2.4 Summary of block shear strength

			Panel 3				Panel 4			
Adhesive	Direction	Treatment	S1	S2	S3	S4	S1	S2	S3	S4
ISO	Major	None	1.38	1.22	7.05	5.53	3.92	1.95	5.17	7.16
		100 Sanding	4.18	6.25	5.68	1.75	6.23	4.78	2.12	4.66
		600 Sanding	1.32		4.2	4.42	3.72	4.36	0.37	1.94
		Tooth-plate	6.6	6.78	6.18	5.01	5.35	5.78	3.33	0.96
		100 Sanding & Tooth-plate	5.69	7.01	6.7	6.46	4.56	5.45	4.34	3.45
		600 Sanding & Tooth-plate	5.26	6	6.13		1.07		6.93	5.19
	Minor	None	6.8	6.22	6.4	7.6	6.71	4.85	8.26	5.03
		100 Sanding	1.47	0.57	1.47	3.13	3.89	4.41	3.88	2.34
		600 Sanding	1.86		2.59	1.95	5.32	4.2	5.45	3.79
		Tooth-plate	7	7.45	6.61	6.14	4.06	3	2.14	0.48
		100 Sanding & Tooth-plate	6.72	6.37	4.83	6.12	3.98	5.4	6	4.28
		600 Sanding & Tooth-plate	8.02	6.14	1.82	2.44	6.38	3.93	5	5.77

Appendix 3.1 Percentage Wood Failure of specimens in major direction

Group		Number of specimens with 4 failure modes				
		glue-line dominant	Wood failure dominant			
		WF<50%	80-89%	90-99%	100%	Total
major	PN-1	0	0	3	5	8
	PN-2	0	1	1	6	8
	PS1-1	1	1	0	6	8
	PS1-2	0	3	0	5	8
	PS6-1	1	1	0	6	8
	PS6-2	0	0	1	7	8
	PT-1	0	0	3	5	8
	PT-2	1	1	0	6	8
	PTS1-1	0	0	1	7	8
	PTS1-2	0	0	3	5	8
	PTS6-1	1	0	2	6	8
	PTS6-2	0	1	0	7	8

Appendix 3.2 Percentage Wood Failure of specimens in major direction

Group		Number of specimens with 4 failure modes				
		glue-line dominant	Wood failure dominant			
		WF<50%	80-89%	90-99%	100%	Total
major	IN- 1	0	0	2	6	8
	IN- 2	1	0	0	7	8
	IS1- 1	1	1	0	6	8
	IS1-2	0	2	2	5	8
	IS6-1	1	0	0	7	8
	IS6-2	0	1	2	5	8
	IT-1	3	1	0	4	8
	IT-2	1	0	1	6	8
	ITS1-1	0	1	2	5	8
	ITS1-2	1	0	0	7	8
	ITS6-1	2	0	0	6	8
	ITS6-2	0	1	0	7	8

Appendix 4.1 Percentage Wood Failure of specimens in minor direction

Group		Number of specimens with 4 failure modes				
		glue-line dominant	Wood failure dominant			
		WF<50%	80-89%	90-99%	100%	Total
minor	PN-1	0	0	1	7	8
	PN-2	0	1	1	6	8
	PS1-1	0	0	0	8	8
	PS1-2	0	1	0	7	8
	PS6-1	1	0	1	6	8
	PS6-2	0	0	3	5	8
	PT-1	0	0	1	7	8
	PT-2	0	0	4	4	8
	PTS1-1	0	0	0	8	8
	PTS1-2	0	2	1	5	8
	PTS6-1	0	0	2	6	8
	PTS6-2	0	1	1	6	8

Appendix 4.2 Percentage Wood Failure of specimens in minor direction

Group		Number of specimens with 4 failure modes				
		glue-line dominant	Wood failure dominant			
		WF<50%	80-89%	90-99%	100%	Total
minor	IN- 1	0	0	1	7	8
	IN- 2	0	0	3	5	8
	IS1- 1	1	0	1	6	8
	IS1-2	1	2	0	5	8
	IS6-1	0	1	1	6	8
	IS6-2	0	0	4	4	8
	IT-1	0	1	0	7	8
	IT-2	0	1	2	5	8
	ITS1-1	1	0	1	6	8
	ITS1-2	0	1	0	7	8
	ITS6-1	1	0	2	5	8
	ITS6-2	0	1	3	4	8

Appendix 5. DOE report and General Linear Model for bending test calculated by Minitab

General Linear Model: Horizontal shear strength versus Adhesive, Surface treatment, Panel direction

Method

Factor coding	(-1, 0, +1)
Rows unused	123

Factor Information

Factor	Type	Levels	Values
Adhesive	Fixed	2	PF, Isocyanate
Surface treatment	Fixed	6	None, 100 Sanding, 600 Sanding, Toohth-plate, 100 Sanding & Tooth-plate, 600 Sanding & Tooth-plate
Panel direction	Fixed	2	major, minor

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Adhesive	1	27.060	27.0600	346.46	0.000
Surface treatment	5	2.898	0.5796	7.42	0.000
Panel direction	1	1.953	1.9525	25.00	0.000
Error	253	19.760	0.0781		
Lack-of-Fit	16	9.937	0.6211	14.99	0.000
Pure Error	237	9.823	0.0414		
Total	260	51.182			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.279470	61.39%	60.32%	58.90%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	2.2430	0.0173	129.54	0.000	
Adhesive					
PF	0.3225	0.0173	18.61	0.000	1.00
Surface treatment					
None	-0.1554	0.0393	-3.96	0.000	1.66
100 Sanding	-0.1251	0.0382	-3.28	0.001	1.62
600 Sanding	0.0209	0.0393	0.53	0.595	1.66
Toohth-plate	0.0396	0.0389	1.02	0.309	1.65
100 Sanding & Tooth-plate	0.1200	0.0375	3.20	0.002	1.60
Panel direction					
major	0.0866	0.0173	5.00	0.000	1.00

Regression Equation

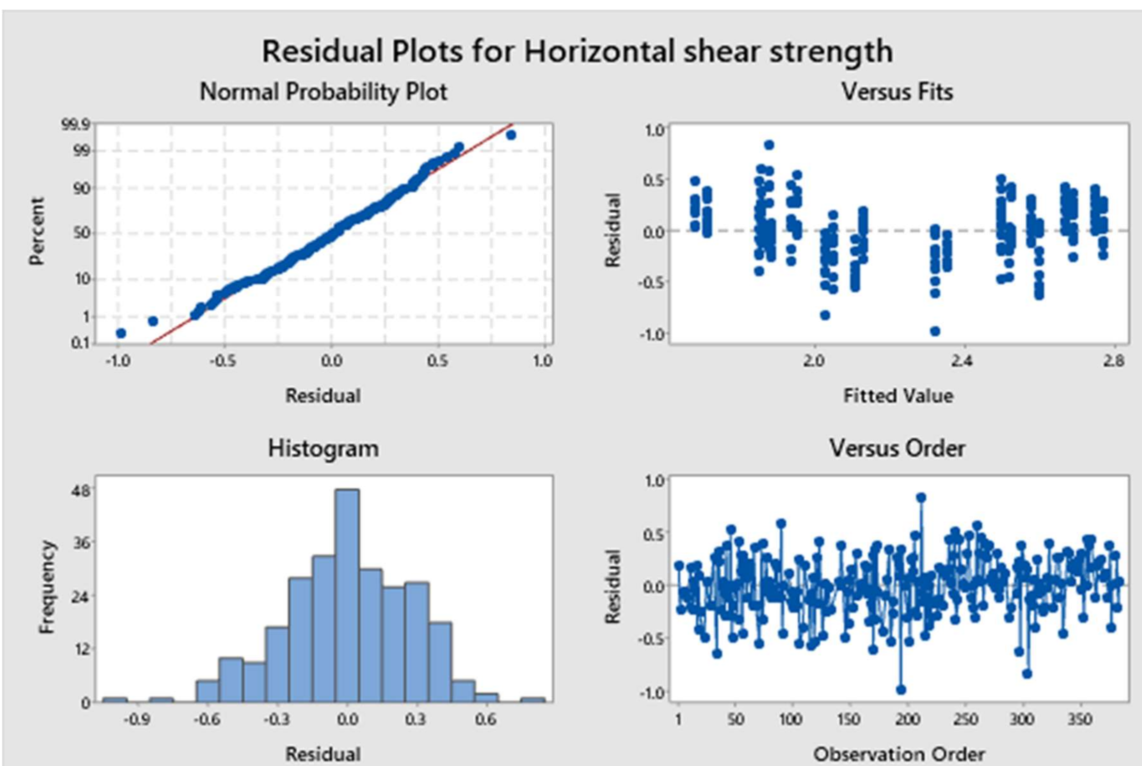
Horizontal shear strength = 2.2430 + 0.3225 Adhesive_PF - 0.3225 Adhesive_Isocyanate - 0.1554 Surface treatment_None -

0.1251 Surface treatment_100
Sanding + 0.0209 Surface treatment_600 Sanding
+ 0.0396 Surface treatment_Toohth-plate
+ 0.1200 Surface treatment_100 Sanding & Tooth-plate
+ 0.1000 Surface treatment_600 Sanding & Tooth-plate
+ 0.0866 Panel direction_major - 0.0866 Panel direction_minor

Fits and Diagnostics for Unusual Observations

Obs	Horizontal shear strength	Fit	Resid	Std Resid
34	1.9600	2.5989	-0.6389	-2.32 R
90	2.4600	1.8548	0.6052	2.20 R
106	2.0400	2.5989	-0.5589	-2.03 R
115	1.4800	2.0467	-0.5667	-2.06 R
170	1.7100	2.3236	-0.6136	-2.23 R
194	1.3300	2.3236	-0.9936	-3.61 R
212	2.7200	1.8736	0.8464	3.08 R
260	2.4600	1.8736	0.5864	2.13 R
298	1.9800	2.5989	-0.6189	-2.25 R
305	1.1900	2.0280	-0.8380	-3.05 R

R Large residual



Appendix 6. DOE report and General Linear Model for block shear test calculated by Minitab

General Linear Model: Shear strength versus Adhesive, Surface treatment, Panel direction

Method

Factor coding	(-1, 0, +1)
Rows unused	134

Factor Information

Factor	Type	Levels	Values
Adhesive	Fixed	2	PF, Isocyanate
Surface treatment	Fixed	6	None, 100 Sanding, 600 Sanding, Toohth-plate, 100 Sanding & Tooth-plate, 600 Sanding & Tooth-plate
Panel direction	Fixed	2	major, minor

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Adhesive	1	42.47	42.4656	27.68	0.000
Surface treatment	5	89.60	17.9200	11.68	0.000
Panel direction	1	32.65	32.6498	21.28	0.000
Error	242	371.32	1.5344		
Lack-of-Fit	16	153.45	9.5909	9.95	0.000
Pure Error	226	217.86	0.9640		
Total	249	534.48			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
1.23870	30.53%	28.52%	25.81%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	4.4020	0.0787	55.96	0.000	
Adhesive					
PF	0.4140	0.0787	5.26	0.000	1.01
Surface treatment					
None	0.235	0.182	1.29	0.198	1.79
100 Sanding	-0.282	0.175	-1.61	0.108	1.73
600 Sanding	-0.151	0.176	-0.86	0.392	1.74
Toohth-plate	-0.973	0.173	-5.62	0.000	1.72
100 Sanding & Tooth-plate	1.006	0.177	5.69	0.000	1.75
Panel direction					
major	0.3622	0.0785	4.61	0.000	1.00

Regression Equation

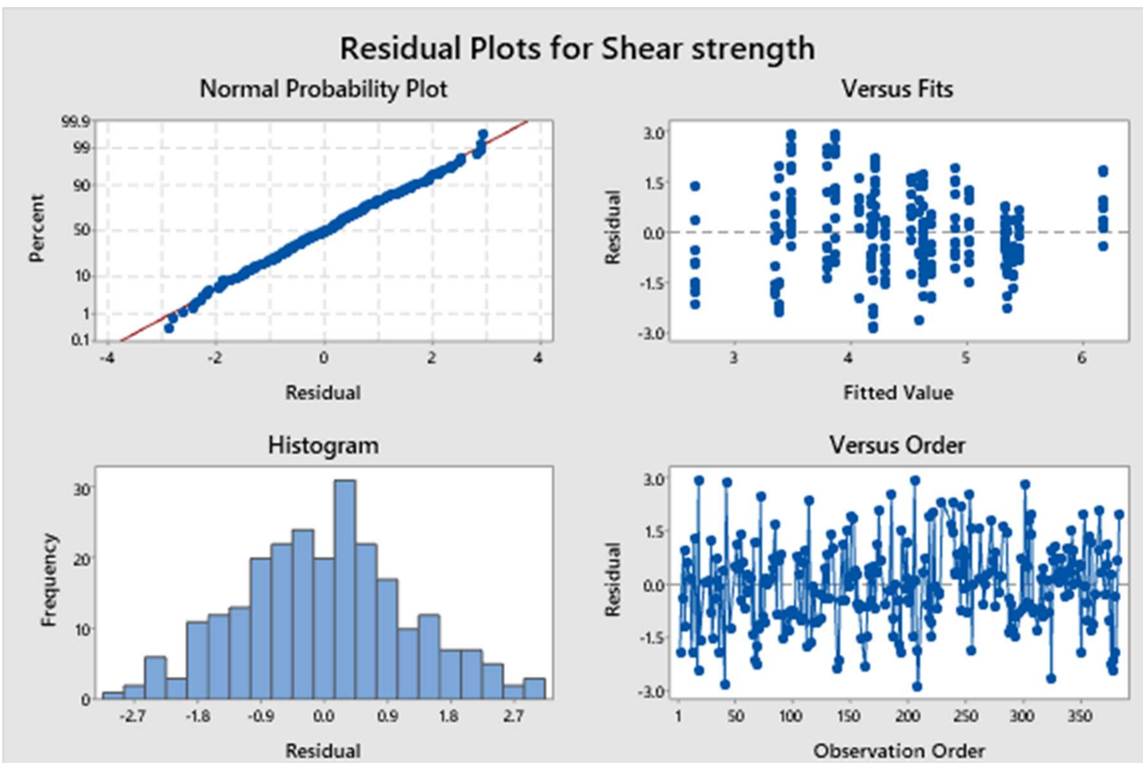
Shear strength = 4.4020 + 0.4140 Adhesive_PF - 0.4140 Adhesive_Isocyanate
+ 0.235 Surface treatment_None - 0.282 Surface treatment_100 Sanding

- 0.151 Surface treatment_600 Sanding - 0.973 Surface treatment_Toohth-plate
+ 1.006 Surface treatment_100 Sanding & Tooth-plate
+ 0.165 Surface treatment_600 Sanding & Tooth-plate
+ 0.3622 Panel direction_major - 0.3622 Panel direction_minor

Fits and Diagnostics for Unusual Observations

Obs	Shear strength	Fit	Resid	Std Resid
17	1.750	4.199	-2.449	-2.01 R
18	6.430	3.474	2.956	2.43 R
41	1.370	4.199	-2.829	-2.32 R
42	6.380	3.474	2.906	2.38 R
72	6.290	3.791	2.499	2.05 R
186	6.040	3.474	2.566	2.11 R
206	6.800	3.861	2.939	2.41 R
209	1.320	4.199	-2.879	-2.36 R
254	6.400	3.861	2.539	2.09 R
302	6.710	3.861	2.849	2.34 R
325	1.950	4.585	-2.635	-2.17 R

R Large residual



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Publications :

1) Ma TY, Ma ZY, Gong M. 2019. Two case studies on non-residential hybrid timber buildings. International Wood Industry, 49(4): 6-11. (in Chinese)