



EXAMENSARBETE INOM BYGGTEKNIK OCH DESIGN
GRUNDNIVÅ 15 HP
STOCKHOLM, SVERIGE 2023

Experimental Investigation of Net-Tension Capacity in Birch Plywood Gusset Plates via Mechanical Connectors and Adhesives

Experimentell undersökning av
nettopänningskapacitet i
björkfanérskivor med mekanisk- och
limförband

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TRITA-ABE-MBT- 23546

Abstract

This thesis examines the mechanical behavior and performance of plywood connections with mechanical connectors and adhesive bonding to glulam. The aim is to provide insights into the capacity and characteristics of these connections for well-founded design decisions in timber structures.

Through a comprehensive literature review, the existing knowledge on plywood-glulam connections and mechanical connectors is explored. Joint configurations, material properties, and testing methods are analyzed to establish a foundation for the experimental investigation.

Experimental tests are conducted on plywood specimens connected with mechanical dowels at different angles to the face grain. The net-tension capacity of birch plywood is evaluated by varying specimen width. The results reveal a capacity plateau at specific widths, indicating optimal connection performance. However, further tests are needed to determine the precise characteristics of the plateau, especially for wider widths uncommon in practical applications.

Analytical predictions are also employed to estimate connection performance. A spreading angle of 11 degrees yields the closest match to experimental results, showcasing the effectiveness of the analytical approach. However, deviations are observed, attributed to factors like local fiber deviations and potential human error. Further investigations are recommended to enhance the reliability of the analytical model.

The thesis also investigates the connection between plywood and glulam via adhesive, tests at different angles yield intriguing results, including a sudden capacity drop at a specific width for zero-degree connections. Surprising phenomena are observed, such as the contrasting behavior of narrower and wider widths in 0-degree and 22.5-degree specimens. Further research is warranted to understand these phenomena and design plywood gusset plates with consistent capacity across all angles.

Analytical predictions for adhesive-bonded connections are limited due to the absence of a capacity plateau. Nonetheless, a spreading angle of 5 degrees is identified as the closest prediction to test results, demonstrating the potential of the analytical approach. Deviations between predicted and observed capacities are acknowledged, underscoring the need for further investigations and consideration of parameters like adhesive types, plywood properties, and alternative joint configurations.

In conclusion, this thesis provides valuable insights into the behavior and performance of plywood connections with mechanical connectors and adhesive bonding to glulam. The experimental and analytical findings contribute to the existing knowledge base and offer practical implications for the design and implementation of these connections in timber structures. Future research can build upon these findings to advance the understanding and design of plywood-glulam connections.

Sammanfattning

Detta arbete undersöker det mekaniska beteendet och prestandan hos plywood-förbindelser med mekaniska kopplingar och limbindning till limträ. Syftet är att ge insikt i kapaciteten och egenskaperna hos dessa förbindelser för välgrundade designbeslut i träkonstruktioner.

Genom en omfattande litteraturgenomgång utforskas den befintliga kunskapen om plywood-limträ-förbindelser och mekaniska kopplingar.

Förbindelseskonfigurationer, materialegenskaper och testmetoder analyseras för att etablera en grund för den experimentella undersökningen.

Experimentella tester utförs på plywood-prover som är anslutna med mekaniska Stavpinne vid olika vinklar mot fibrerna. Nettodragkapaciteten hos björkplywood utvärderas genom att variera provets bredd. Resultaten avslöjar en kapacitetsplatå vid specifika bredder, vilket indikerar optimal förbindelsesprestanda. Ytterligare tester krävs dock för att fastställa de exakta egenskaperna hos platån, särskilt för bredare bredder som är ovanliga i praktiska tillämpningar.

Analytiska förutsägelser används också för att uppskatta förbindelsesprestanda. En spridningsvinkel på 11 grader ger den närmaste matchningen med experimentella resultat och visar effektiviteten hos den analytiska metoden. Avvikelse observeras dock, vilket tillskrivs faktorer som lokala fiberavvikelse och potentiella mänskliga fel. Vidare undersökningar rekommenderas för att förbättra tillförlitligheten hos den analytiska modellen.

Avhandlingen undersöker även förbindelsen mellan fanérträ och limträ där lim används för sammankopplingen mellan dessa två material, tester vid olika vinklar ger intressanta resultat, inklusive en plötslig kapacitetsminskning vid en specifik bredd för förbindelser vid noll grader. Överraskande fenomen observeras, som det motsatta beteendet hos smalare och bredare bredder i 0-graders och 22,5-graders prov. Vidare forskning behövs för att förstå dessa fenomen och utforma plywood-plattor med jämn kapacitet för alla vinklar.

Analytiska förutsägelser för limmade kopplingar är begränsade på grund av frånvaron av en kapacitetsplatå. Trots detta identifieras en spridningsvinkel på 5 grader som den närmaste förutsägelsen till testresultat, vilket visar potentialen hos den analytiska metoden. Avvikelse mellan förutsagda och observerade kapaciteter erkänns och understryker behovet av ytterligare undersökningar och beaktande av parametrar som limtyper, plywood-egenskaper och alternativa förbindelseskonfigurationer.

Sammanfattningsvis ger denna avhandling värdefulla insikter om beteendet och prestandan hos plywood-förbindningar med mekaniska kopplingar och limbindning till limträ. De experimentella och analytiska resultaten bidrar till den befintliga kunskapsbasen och erbjuder praktiska implikationer för design och implementering av dessa förbindningar i träkonstruktioner. Framtida forskning kan bygga vidare på dessa resultat för att främja förståelsen och designen av plywood-limträ-förbindningar.

Preface

I am deeply grateful to express my sincerest appreciation to the remarkable individuals who have played a significant role in shaping my academic journey and making this thesis a reality. Their unwavering support and profound impact have been instrumental in my growth and achievements.

Foremost, I want to express my heartfelt gratitude to my mother, whose unwavering love and support has been the cornerstone of my life. She selflessly nurtured and guided me, providing unwavering encouragement during times of adversity and ensuring my success. Her belief in me fueled my determination to overcome challenges and pursue my dreams. Without her, I would not have been able to embark on this transformative journey.

I am also indebted to Sweden, a nation that welcomed me with open arms and offered me a second chance at life. The generosity and support I received from this country are beyond measure. It is an honor to have been granted the opportunity to study at KTH, a prestigious institution that has empowered me with knowledge, skills, and an environment conducive to academic excellence. I am forever grateful for the immense privilege of graduating under its esteemed name.

My heartfelt appreciation also extends to the incredible friends I have had the fortune of meeting during my time in Stockholm. Their companionship, warmth, and unwavering support have enriched my experience, making every day a cherished memory. Their presence has been a source of strength and inspiration throughout this journey.

I would like to express my deepest gratitude to Yue and Tianxiang, whose enormous help and dedicated supervision have been invaluable to the completion of this thesis. Their expertise, guidance, and unwavering commitment to my academic growth have been truly remarkable. I am truly fortunate to have had their mentorship and support.

Lastly, I would like to acknowledge all those who have offered their encouragement and support, whether through kind words, motivation, or a helping hand. Your belief in my abilities and unwavering faith have been a constant source of motivation and inspiration.

To all the individuals who have shaped my path, I offer my heartfelt gratitude. This thesis stands as a testament to the collective effort and dedication of everyone involved. May this work contribute to the broader discourse in its field and inspire others to strive for excellence, embrace challenges, and make a meaningful impact in their respective areas of study.

In sincere appreciation,

Ibrahim Abd Ullah Alhamo

First and foremost, I am profoundly thankful to members of my family for their unwavering belief in me and the unconditional support they have provided throughout this endeavor. Their constant encouragement and sacrifices have fueled my determination and motivated me to pursue excellence in my studies.

I am immensely grateful to KTH for providing me with a remarkable opportunity to pursue my academic aspirations. The institution's commitment to academic excellence, coupled with its vibrant intellectual environment, has nurtured my passion for knowledge and pushed me to new heights. I extend my sincere appreciation to the dedicated staff and faculty members who have contributed to creating a conducive learning environment.

To my cherished friends, I want to express my heartfelt appreciation for their unwavering presence and camaraderie. Their support, laughter, and shared experiences have not only made this journey more enjoyable but have also served as a source of inspiration during challenging times. Your friendship has brought warmth and joy to every step of this academic pursuit.

I am indebted to the exceptional guidance and mentorship of Yue and Tianxiang throughout this thesis. Their expertise, patience, and unwavering commitment to my academic growth have been invaluable. Their insights and feedback have helped refine my research and elevate the quality of this work. I am truly grateful for their guidance and the immeasurable impact they have had on my scholarly development.

Finally, I want to express my sincere appreciation to all those who have contributed to my journey, be it through words of encouragement, intellectual discussions, or practical assistance. Your belief in my abilities and your unwavering support have been a constant source of motivation, and I am deeply grateful for your contributions.

In conclusion, I humbly offer my heartfelt gratitude to each person who has played a role in my academic journey. This thesis stands as a testament to our collective efforts and represents a milestone in my intellectual growth. With profound appreciation, I present this work as a humble contribution to the field, with the hope that it sparks further exploration and advances in knowledge.

With sincere thanks,

Farid Mobin

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Abbreviation

EWP	Engineered wood product
LVL	Laminated veneer lumber
CLT	Cross-laminated Timber
OSB	Oriented strand board
MC	Moisture content
COV	Coefficient of variation
PRF	Phenol–Resorcinol– Formaldehyde Adhesive

Symbols

A	Cross-sectional area	$[m^2]$
t	Thickness of plywood	$[m]$
w	Width of birch plywood	$[m]$
w_{eff}	Effective width	$[m]$
f_t	Tensile strength	$[Nm^{-2}]$
F	Applied force	$[N]$
F_a	Assumed force capacity	$[N]$
R^2	coefficient of determination a statistical method	

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1 Introduction

Timber is an important material in the construction industry and has been used as a structural element for centuries. Its natural properties offer several advantages over other materials such as steel and concrete, including its low environmental impact, high strength-to-weight ratio, and renewable nature. In recent years, there has been renewed interest in the use of timber as a sustainable and viable building material, leading to a growing body of research on the structural properties and performance of timber elements. This paper focuses on the use of timber as structural elements, specifically exploring its potential as a component of gusset plates. Through an experimental investigation of the net-tension capacity of birch plywood gusset plates using mechanical connectors and adhesives, this study aims to contribute to the existing knowledge on the structural behavior of timber elements and inform best practices for their use in construction.

1.1 Timber as structural elements

Timber has been used in structures for thousands of years, and it continues to be a popular material today due to its aesthetic and environmental benefits. Timber has several advantages over other building materials, such as its strength-to-weight ratio, ease of construction, and renewable nature. However, the utilization of timber in structures is also affected by several factors such as moisture content, strength, and decay resistance.

The moisture content of timber plays a significant role in its strength and stability. Moisture can cause timber to expand and contract, which can lead to cracking, warping, and distortion. Effective drying and treatment of timber can reduce its moisture content and enhance its stability. Timber with lower moisture content is also more resistant to decay and insects, making it a more durable building material.

Strength is another crucial factor to consider when using timber in structures. The strength of timber varies depending on its species, grade, and size. Structural timber is typically categorized based on its strength properties, such as bending strength and compressive strength. The use of laminated timber can also enhance its strength, as high-grade material can be used in regions of high stress.

Timber is also susceptible to decay and insect damage, which can compromise its structural integrity. To prevent this, timber can be treated with preservatives that penetrate the wood and protect it from decay and insects. The type and level of treatment required depend on the intended use and the level of exposure to moisture and insects.

In addition to its technical properties, the usage of timber in structures is also influenced by its aesthetic and environmental benefits. Timber has a natural beauty that can enhance the appearance of a building, and it is a renewable resource that can contribute to sustainable construction practices. The use of timber in structures can also reduce the carbon footprint of a building, as timber stores carbon and requires less energy to produce than other building materials.

Despite its advantages, the usage of timber in structures is not without challenges. The supply of high-quality timber can be limited, and its cost can be higher than other building materials.

Timber is also more susceptible to fire than other materials, and fire protection measures must be taken to ensure the safety of occupants.

In conclusion, timber is a versatile and environmentally friendly material that has been used in structures for centuries. Its usage is affected by several factors, such as moisture content, strength, and decay resistance, which must be carefully considered during construction. While it has several advantages over other building materials, its usage is not without challenges, and proper measures must be taken to ensure its safety and durability (ANDREWS, 1967).

1.2 Engineered wood products (EWPs)

Engineered wood products (EWPs) are a family of wood-based materials that are created by combining strands, fibers, veneers, or layers of wood with adhesives or other bonding agents. They are designed to provide superior structural performance, increased design flexibility, and improved durability compared to traditional solid wood products. Examples of EWPs include laminated veneer lumber (LVL), glued laminated timber (glulam), cross-laminated timber (CLT), and oriented strand board (OSB). EWPs are widely used in residential, commercial, and industrial construction applications due to their strength, dimensional stability, and sustainability.

1.2.1 Glue laminated lumber (glulam)

Glulam (structural glued-laminated timber) is a stress-rated structural product made up of two or more layers of lumber called laminations. It is defined by ASTM D3737 Standard Method for Establishing Stresses for Structural Glued-Laminated Timber (Glulam) as "a material glued up from suitably selected and prepared pieces of wood either in a straight or curved form with the grain of all pieces essentially parallel to the longitudinal axis of the member." The laminations typically have a nominal thickness of 45 mm, see figure 1 as an example of glulam.



Figure 1 Picture of Glue laminated lumber block contains five blocks of wood that are glued together.

Various species and species combinations, including softwoods and hardwoods, can be used for Glulam as long as their mechanical and physical properties are suitable and their lumber can be glued to meet the requirements. The size of a Glulam member can be limited by the capabilities of the manufacturing plant and the height and width restrictions imposed by the transportation method (Smulski, 1997).

1.2.2 Cross-laminated timber (CLT)

Cross laminated timber (CLT) is an engineered timber product that is composed of an uneven number of layers arranged crosswise to each other at a 90-degree angle and quasi-rigidly connected by adhesive bonding. It is optimized for bearing loads in and out-of-plane, making it a versatile product. Due to the continuous bonding between the layers, it creates a compact and versatile usable product. CLT can be used for large-sized wall and floor elements, linear structural components, and monolithic buildings (Brander, 2013).

CLT opens new dimensions in timber engineering and allows architects and engineers to design and construct buildings to previously unknown dimensions and scales. The product has been in development for about two decades and has rapidly grown in production capacities, with a current production volume of roughly 500,000 m³/a (2012) worldwide, mainly in Austria and Germany (Brander, 2013).

The advantages of CLT as a building material include its outstanding capability for pre-fabrication, dry and clean construction technique, and short erection times on-site. The product's high dimensional stability underlines accuracy, with the lowest tolerances well-known for timber construction in general. It is ideal for reconstruction and upgrading of existing buildings and also for resisting exceptional loadings such as earthquakes (Brander, 2013).

CLT is also advantageous in that it has a clear separation of load-bearing from insulation & installation layers, low air permeability, distinctive specific storage capacity for humidity and temperature, independence of modular dimensions in arranging window and door openings, and advantages in fastening services and furniture. The product's low mass, stiffness, and bearing capacity against in-plane and out-of-plane stresses make it ideal for multi-storey residential and office buildings, schools, single-family houses, halls, the conversion and upgrading of existing buildings, and wide-span structures such as bridges (Brander, 2013).

In Norway, Treet building is a remarkable example of a tall wooden structure made primarily of cross-laminated timber. Treet, which translates to "the tree" in Norwegian, is an urban housing project located in Bergen, Norway, and stands at a height of 14 stories, as shown in figure 2.

Completed in 2015, the Treet building was hailed as the tallest timber building in the world at the time of its completion. The building

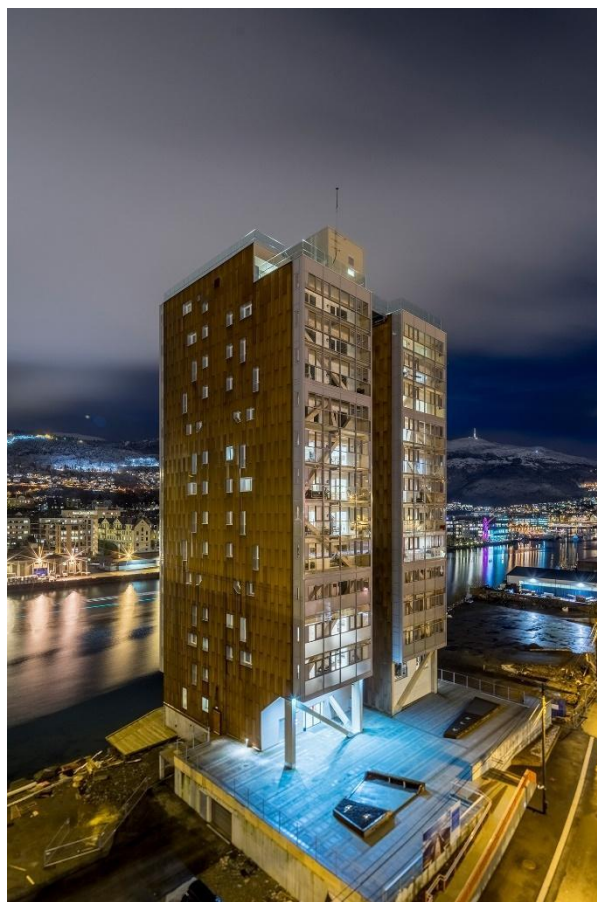


Figure 2 ARTEC. Treet building in Norway. Retrived from ARTEC website (ARTEC, 2023).

consists of 62 apartments, with commercial spaces on the ground floor, and it was designed with a focus on energy efficiency and sustainability.

Treet's construction utilized 3,500 cubic meters of wood, primarily spruce, which was sourced from sustainably managed forests in Norway. The use of wood in the building's construction allowed for a significant reduction in carbon emissions compared to traditional building materials such as concrete and steel.

The Treet building also incorporates a range of energy-saving features, including triple-glazed windows, solar panels, and a ventilation system that uses recovered heat to warm the building. These features have contributed to Treet being awarded the highest energy rating for buildings in Norway (Abrahamsen, 2015).

Overall, CLT has opened new possibilities in timber engineering, making it possible to design and construct buildings to previously unknown dimensions and scales. Its advantages make it an ideal building material for a range of structures, from small and medium buildings to wide-span structures like bridges.

1.2.3 Plywood and other structural panels

Plywood is a type of engineered wood product that is commonly used in construction, furniture making, and packaging. The most common type of plywood is veneer plywood, which is made up of several layers of thin wooden veneers that are cross laminated to even out the material's strength and moisture resistance. Other types of plywood include composite plywood, which can have layers of non-wood materials, and laminated plywood, which has inner layers of wooden strips between veneer layers. The choice of wood and adhesive type determines the specific use of the plywood, with different grades and treatments available for various applications such as building, furniture making, and marine construction. The quality of the raw veneer and the finished plywood is also graded based on factors such as surface smoothness, strength, and resistance to weather and moisture (NE, u.d.).

The shortage of wood as a raw material in the wood-based industry has led to a search for alternative sources of local raw materials, and oil palm biomass has emerged as a viable option. One promising application is the production of plywood from oil palm biomass, specifically oil palm trunks and empty fruit bunches. The production of hybrid plywood from these materials has been successfully demonstrated and offers several advantages such as low density, biodegradability, and low cost. This innovative approach to plywood production not only helps to mitigate environmental problems from waste biomass but also provides an alternative to wood, which is becoming increasingly scarce (Abdul Khalil, Nurul Fazita, Bhat, Jawaaid, & Nik Fuad, 2010), please refer to figure 3 (a plywood plate with seven veneers).



Figure 3 Birch Plywood with seven veneers. Photo taken by Ibrahim Abd Ullah Alhamo.

Birch plywood has been found to have high tensile, compressive, and bending strength as well as elastic modulus parallel to the face grain. This makes it a strong candidate for new types of connections for timber structures, which could potentially replace the current system with steel plates. Not only would this result in significant advantages in terms of environmental impact and economy, but it would also make prefabrication and mountability easier (WANG, 2022).

However, there is a need for more data concerning some of the mechanical properties of plywood in directions other than along and perpendicular to the face grain, so that safe design can be performed. The variation of the in-plane mechanical properties of plywood at different loading angles to the face grain needs to be studied further to fully understand its potential as a replacement for steel plates.

1.3 Timber connection

Timber connections are used to join pieces of timber together to form structures. These methods range from traditional joints to modern steel connectors, and adhesive bonding. Properly designed connections are crucial for the safety and durability of timber structures.

1.3.1 Carpentry connection

Carpentry joints used in traditional timber framing can be classified into four types: tenon and mortise joints, notched joints, lap joints, and scarf joints. Tenon joints connect members at an angle between 45° and 90° using a mortise hole and a tenon tongue. The joint may be pinned or locked into place. Notched joints are V-shaped grooves cut into the timber to provide secure footing for the toe of a rafter or strut or between the rafter and the king-post. Lap joints can be full or half, with the thickness of the resulting joint equaling the combined thickness of the two members or the same as that of the thickest member, respectively. Scarf joints splice two members end to end and are mainly used when the material being joined is not available in the

required length. These techniques have been used for centuries in timber framing and continue to be relevant in modern construction for their strength and durability (Branco & Descamps, 2015 Oktober), See figure 4.

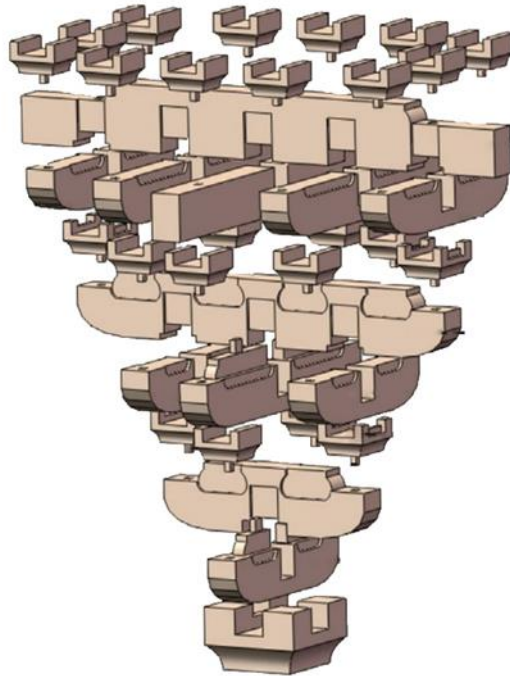


Figure 4 A detailed traditional connection (Dou-Gong) dated back to the pre-Ming dynasty (Meng, Yang, Wei, & Li, 2018).

1.3.2 Mechanical connection

Steel plates are widely used in various construction applications due to their excellent strength, durability, and ease of fabrication. They are commonly used to strengthen timber structures through mechanical connections. In large-scale timber structures and high-rise timber buildings, steel plates slotted into cut-outs in timber elements are often used in combination with dowel-type connections to enhance the load-carrying capacity and stiffness of connections. Typical examples of mechanical fasteners include dowels, screws, bolts, and nails.

However, plywood plates could be an alternative to slotted-in steel plates. Compared to steel plates, plywood plates are competitive in structural connections due to their low carbon footprint, high tolerance during assembly, relatively low cost and less prefabrication demand.

Please refer to Figure 5 on Page 7, which illustrates a mechanical connection using slotted rods passing through wood and steel.



Figure 5 Mechanical connection taken by D. Scott Nyseth (Nyseth, 2020)

1.3.3 Adhesively bonded connection

Adhesives play a crucial role in the timber industry. As mentioned in Adhesive bonding (Serrano & Källander, 2005), adhesives are used to create strong and durable bonds between timber components, which can improve the structural integrity and lifespan of timber structures. This is especially important in engineered wood products, such as glulam beams and cross-laminated timber (CLT), where several pieces of timber are bonded together to create a larger, stronger structure.

Phenol-resorcinol-formaldehyde (PRF) is highly resistant to moisture and temperature, making it a conventional choice for glulam production in Sweden. In recent years, melamine-urea-formaldehyde (MUF) takes a considerable hold in the glulam industry with esthetic and economic advantages compared to PRF. Other types of adhesives used in timber construction include polyurethane and epoxy, etc.

In addition to improving the structural performance of timber structures, adhesives can also enhance their fire resistance. For example, fire-retardant adhesives can be used to increase the fire resistance of engineered wood products (Serrano & Källander, 2005).

However, it's important to note that the quality of the bond between the adhesive and the timber can be influenced by several factors, including moisture content, temperature, and surface preparation. Therefore, it's essential to follow proper bonding procedures and use the appropriate adhesive for the specific application to ensure a strong and durable bond (Serrano & Källander, 2005).

It is important to acknowledge that mechanical joints can exhibit reduced stiffness due to clearance between the fastener and the hole, as well as bending deformation of the fastener (Imakawa, o.a., 2022). This well-recognized issue prompted the development of an alternative connection method using adhesives. Properly bonding plywood plates to timber components

within a joint can lead to enhanced stiffness and load-bearing capacity compared to mechanical connections using dowel-type fasteners (Wang T. , o.a., 2023).

1.4 Aim and scope of this thesis

1.4.1 Problem initiation

Richard E. Whitmore, an American researcher, discovered that the stress distribution on a steel plate near the diagonal member (upper left) can be depicted by the stress contour shown in Figure 7. This was revealed in his paper titled "Experimental Investigation of Stresses in Gusset Plates," and the experimental arrangement is presented in Figure 6.

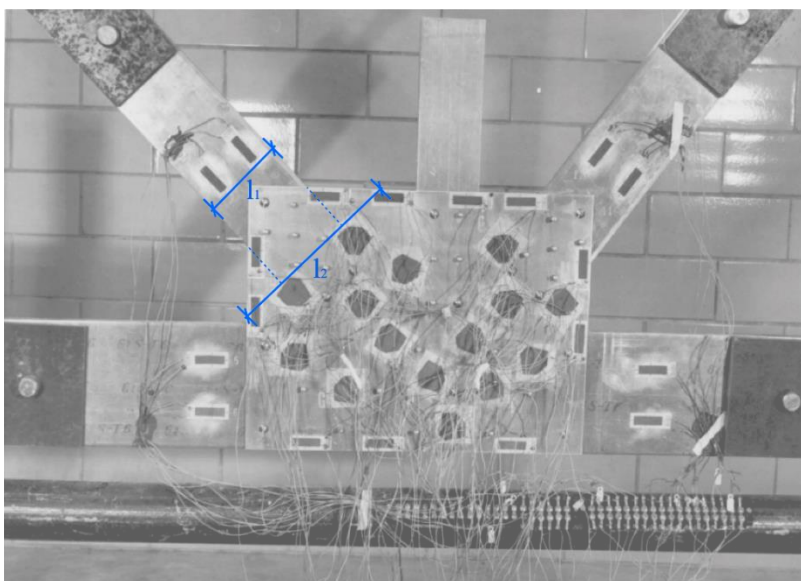


Figure 6 The experimental set-up in the study of R. E. Whitmore (Whitmore, 1950)

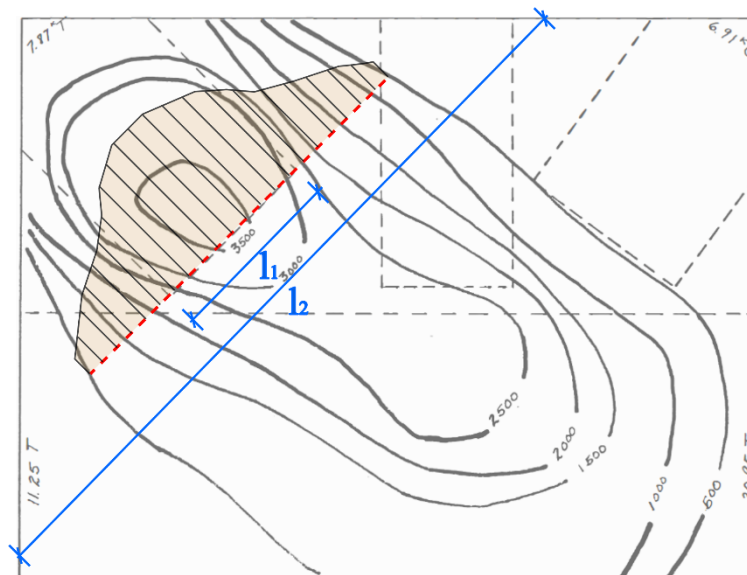


Figure 7 The stress distribution contour on the steel joint plate that was imposed by the tension from the upper left member (Whitmore, 1950).

As depicted in Figure 6, the application of force from the diagonal member onto the joint plate results in uneven stress distribution along the width of the loaded cross-section, spreading from the central jointing position to the edge (as shown by the red line in Figure 7). R. E. Whitmore observed this phenomenon on steel plates.

If we assume a constant design value for the member's load-bearing capacity, R_d , an appropriate design for the steel plate should consider the effective stress distribution range (represented by the red dashed line in Figure). However, the length of the effectively loaded width still needs to be determined.

Suppose the designer considers only the loaded width of the joint plate to be equal to the width of the diagonal beam, l_1 , which is shorter than the red dashed line (indicated by blue coloring in both Figure 6 & 7). In that case, the plate thickness is calculated as:

$$t_1 = \frac{R_d}{f_t \cdot l_1} \quad (1)$$

where f_t represents the material's tensile strength. This would result in an excessively conservative design with a thick plate and a considerable waste of material.

On the other hand, if the loaded width of the joint plate is considered to be equal to the length on the plate along the end side of the diagonal member, l_2 , which is longer than the red dashed line (as shown in both Figure 6 & 7), the plate thickness is designed as shown in equation 1 (where f_t represents the material's tensile strength). However, assuming that the load is evenly distributed along the entire width of l_2 is inaccurate since, as mentioned earlier, stress distributes unevenly within the red dashed line. Consequently, the plate thickness would be insufficient, rendering the design unsafe.

A similar phenomenon was observed on birch plywood plates by Tianxiang Wang and Yue Wang (Wang Y. , o.a., 2023).

This bachelor thesis aims to investigate the stress distribution width limit of birch plywood plates when subjected to uniaxial tension. To achieve this, a series of tests were conducted on birch plywood plates with varying widths, applying uniaxial tension until a force plateau was reached, indicating that the length of the "red line" for birch plywood boards had been surpassed. The results will be used to propose prediction models for deriving a general principle for designing the net-tension capacity of birch plywood plates.

1.4.2 Mechanical properties of birch plywood

Birch is widely spread in Scandinavian countries, in Sweden birch reforming more than 12% of the total forest mass with 411 million m³sk (cubic meter forest) (FöreningenSkogen, u.d.). It is also promising in connection applications, due to the combined advantages of its superior mechanical properties and the cross lamination configuration, which provides satisfactory strength and stability in all in-plane directions

1.4.3 Mechanical connection and adhesively bonded connection

Two types of connections with birch plywood plates, namely, mechanical connection and adhesively bonded connections were investigated in this thesis work. In order to study the

influence of the plywood width on the tensile capacity of the gusset plates, thin birch plywood panels (6.5 mm and 9 mm-thick) were selected and designed as the weakest link in the connection. Hence, tensile failure of the plywood plate was expected.

2 Materials and methods

Experimental studies were conducted in this research. The tests were divided into two types: specimens with mechanical connectors and specimens with adhesive bonded connections. Each type was further divided into three angles (0, 22.5, and 45 degrees), and for each angle, different widths ranging from 52 mm to 350mm were used depending on the type of connection. Three repetitions were conducted for each test series to ensure more reliable results. While additional repetitions could have been beneficial, they were limited due to economic constraints and the relatively small expected differences. Thus, a decision was made to limit the repetitions to three.

2.1 Plywood specimens with mechanical connectors

The studied birch plywood is a commercial product produced by Koskisen (Järvelä, Finland). For the test series with mechanical connectors, the utilized plywood is composed of 7 veneers, with a nominal thickness of 9 mm. The inner 5 veneers have identical thicknesses, while the face veneers are slightly thinner due to the fact that the surfaces of the plywood were sanded during the panel processing in the production line to control the total thickness. Phenol formaldehyde resin was used as an adhesive between each veneer (Gulbrandsen, 2012).

2.1.1 Manufacture and assembly

The utilized birch plywood plates in this study were all manufactured using a table saw with angle guides, as shown in figure 8 below. The principal direction of the birch plywood was referred to as the face grain direction. Off-axis specimens were manufactured using the angle guides on the table saw.



Figure 8 cutting the plywood plate to desired dimensions using the saw table.

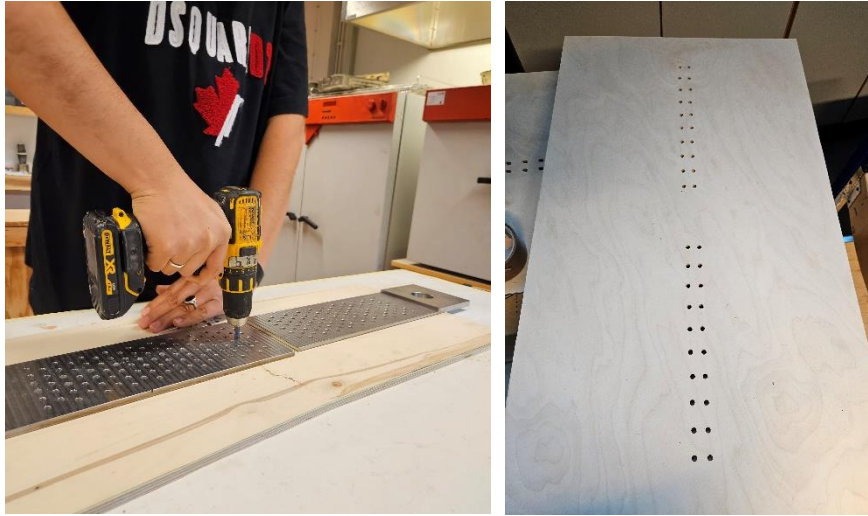


Figure 9 Illustrates the manufacturing process of the birch plywood test pieces.

Afterward, the plate was placed on the plywood to guide the drill in creating holes where the dowels pass through, as illustrated in Figure 9 above.

The test series with mechanical connectors are presented in Table 1. In total, 72 mechanically connected birch plywood plates were tested under uniaxial tension.

Table 1 Birch plywood specimens with mechanical connectors tested in this thesis.

<i>Face grain angle</i>	<i>Total width of birch plywood plate (mm)</i>	<i>Test replicates per series</i>
0°	52, 70, 88, 106, 124, 142, 160, 178, 232, 304, 340	3
22.5°	52, 88, 124, 160, 196, 268, 340	3
45°	52, 88, 124, 196, 340	3

2.1.2 Experiment procedure

Pairs of steel plates are manufactured as apparatus to fix the birch plywood specimens on the testing machine. Smooth dowels from RS Components (RS, 2023) with a nominal diameter of 6 mm and a length of 40 mm are adopted in this study as mechanical connectors between the birch plywood and the steel plates. Detailed configuration is shown in figure 10. (in (a) and (b) only half of the specimen is shown for efficient space and to make it clearer).

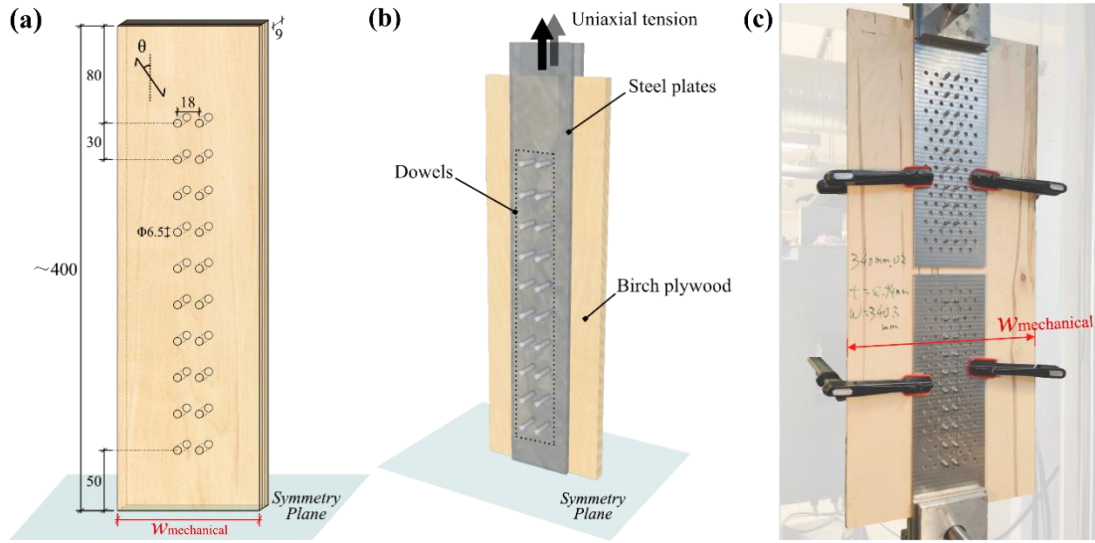


Figure 10 a) Detailed specimen dimensions, b) apparatus setup, and c) test picture of birch plywood specimens with mechanical connectors (unit: mm).

the tests were performed on a universal testing machine MTS 810 with a capacity of 100 kN as shown in figure 11. For mechanical specimens, the movement of the loading head was kept constant with the rate of 2.0 mm/min throughout the tests, so that the specimens broke within 3-10 minutes after the test started. The load signals were recorded using a supplementary load cell.

As mentioned earlier in the Introduction Section, this thesis aims to determine the magnitude of the so-called effective width when the birch plywood plate being subjected to uniaxial tension. Practically, destructive tests were conducted on birch plywood specimens with various widths (denoted as red fonts in figure 7, until a force plateau was reached. Thereafter, the ultimate capacity data was plotted and analyzed versus the variation of plate widths.

The detailed test results are presented in the results and discussion section.

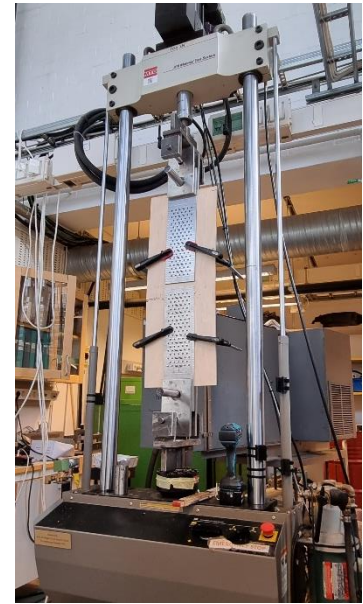


Figure 11 Universal testing machine MTS 810.

2.2 Plywood specimens bonded with adhesive

As for adhesive-bonded specimens, the studied birch plywood consists of 5 veneers with a nominal thickness of 6.5 mm. In order to reach net-tension failure in plywood plates instead of adhesive failure, relatively thin birch plywood was utilized for adhesive specimens. Similarly, as mentioned above, three different loading angles to the face grain were tested with the interval of 22.5°, i.e., 0°, 22.5°, and 45°, with 3 replicates for each test group.

2.2.1 Manufacture and assembly

For this study, GL28cs (EN 14080 2013) spruce glulam beams with dimensions of 42 mm × 180 mm from Moelven (Töreboda, Sweden) were used.

PRF (Aerodux 185/ HRP 155) (Dynea, Lillestrøm, Norway) is the adhesive used in this study. Table 2 presents the mixing ratio, solid content, application amount, assembly time, pressing temperature, and pressing time for the adhesives used in the study, based on technical data and results from a previous study (Wood Material Science & engineering). Open assembly time refers to the period from glue application to assembly, while close assembly time indicates the time from assembly to pressure establishment.

Table 2 PRF parameters related to the process.

<i>Mixing ratio (adhesive: hardener) (pbw)</i>	5:1
<i>Solid content (%)</i>	55-61
<i>Application amount (g/m²)</i>	400
<i>Open assembly time (min)</i>	<5
<i>Close assembly time (min)</i>	40
<i>Pressing temperature (°C)</i>	20
<i>Pressing time for the two clamping methods (hour)</i>	24

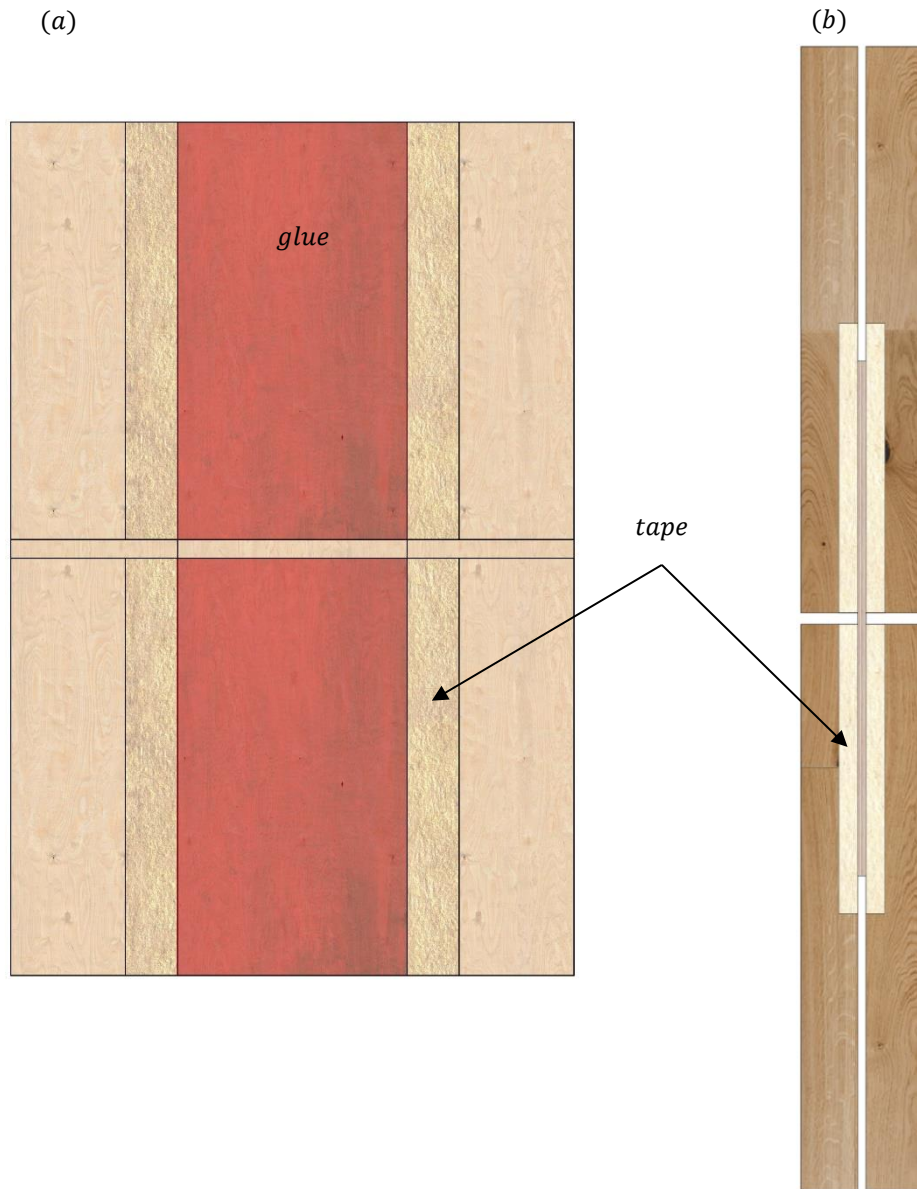


Figure 12 (a) Shows the taped area on the plywood plate, (b) shows the taping on glulam on a specimen (side view).

The process for producing birch plywood plates is akin to mechanical connection, as detailed in section 2.1.1. the only difference is the thinness of birch plywood for this connection is 6.5 mm which is thinner compared to mechanical connection (9 mm) to ensure failure prior to any damage occurring to the glulam beams. Four pieces of glulam are required, which are produced utilizing a table saw machine with the grain direction parallel to the loading axis.



Figure 14 saw table cutting the 225 mm glulam to half (110 mm).

(a)



(b)



(c)



(d)



Figure 13 (a) sanding the surfaces, (b) cleaning the dust after sanding, (c) marking the needed dimensions for the glue, (d) taping

The subsequent stage involves sanding the surfaces where adhesive will be applied to keep the surface clean, see figure 13 (a) and (b). A region measuring 200 mm x 110 mm is marked on each bonding surface of the glulam. The same approach is applied to plywood, except that measurements are taken from both ends of each side to create an adhesive-free space in the middle by 9 mm, as shown in figure 13 (c).

The next step involves taping the sides of the glulam beams and plywood in accordance with the provided photos. This is done to prevent any excess adhesive from seeping onto the sides and bonding the wooden guide, glulam, and plywood. The wooden guide is utilized to keep the pieces in place after the adhesive is applied, please refer to figure 12 showing a detailed taping area and figure 13 (d).

After the taping is completed, the glulam beams can be placed next to each other, with the plywood on top of two glulam beams, as shown in the provided pictures. The adhesive can now be applied, but it must be mixed first. The mixing ratio is 5:1 (parts-by-weights) between the adhesive and the hardener.

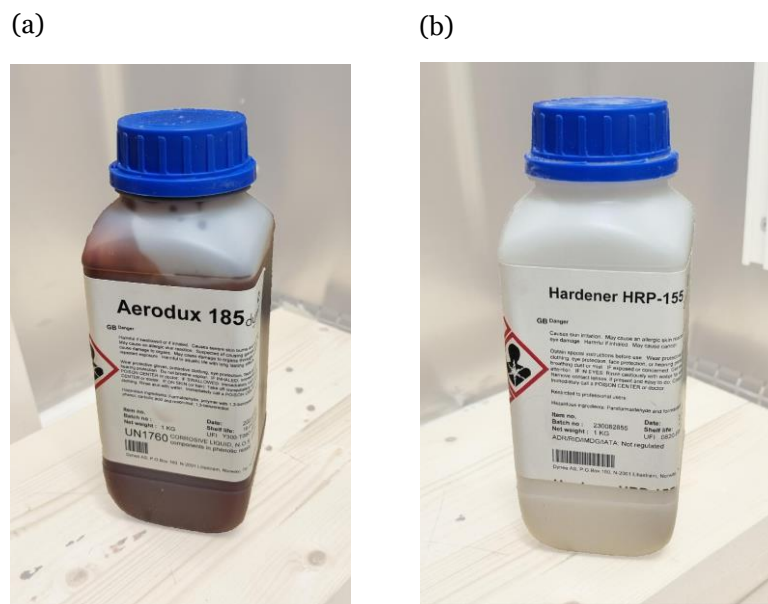


Figure 15 (a) PRF adhesive, (b) the hardener.

The final step involved the application of adhesive. All adhesive types were applied to both glulam and plywood surfaces with an application amount of 400 g/m² on each surface, the adhesive were mixed with hardner, see figure 15 that shows the adhesive and the active hardner. Initially, adhesive was applied to four surfaces, two of the glulam and one side of the plywood. Subsequently, the plywood was placed on top of the glulam and the process was repeated for the other four surfaces. The remaining two glulam beams were then placed on the other side of the plywood. Wooden guides were used to ensure that all parts were properly aligned. Two clamps were placed on the wooden guide to hold everything together.

After 40-minute close assembly time, the rest of the clamps were added on top of the beams as shown in figure 16. All clamps were removed after 24 hours. Thereafter, four screws were

placed into the beam, as shown in figure 17. This extra measure was taken to avoid adhesive bond failure before plywood breaks, as observed in two tests. The screws are supposed to take the potential peeling stress during the tests.

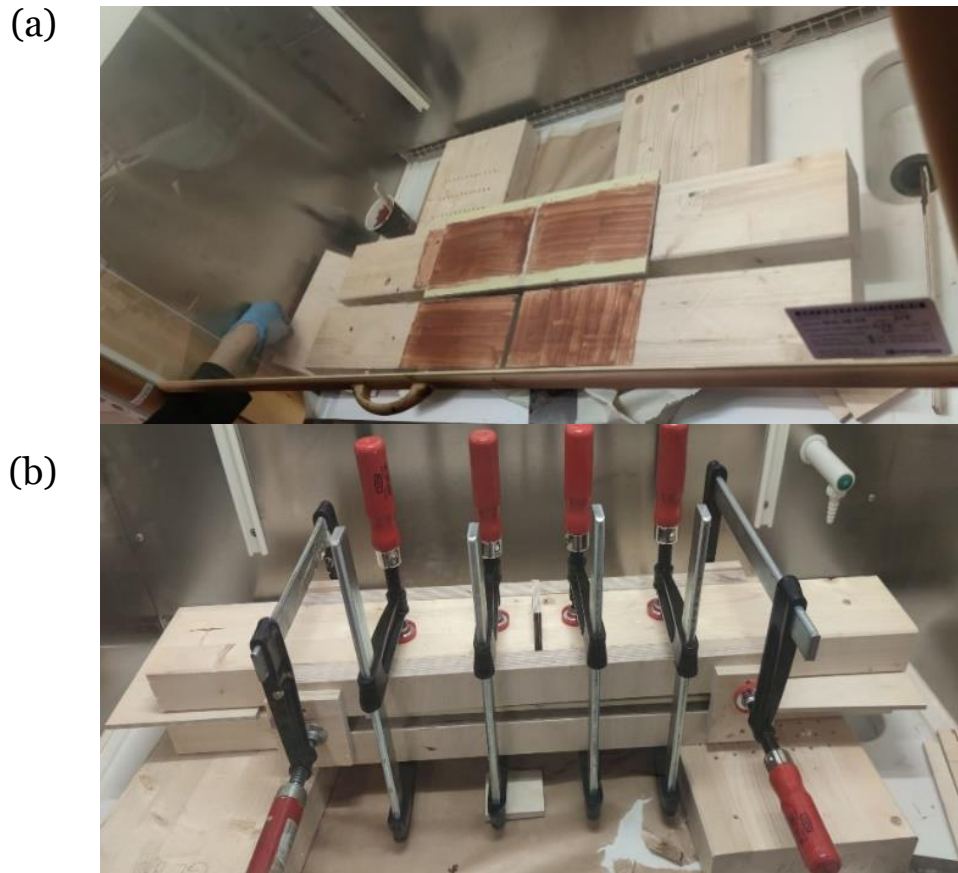


Figure 16 (a) specimen gluing, (b) clamping the specimen.



Figure 17 inserting the screw to take the peeling stress.

After 24 hours the clams were taken off and the specimen was ready for drilling. Two holes were made at the end of the specimen (refer figure 18 below) to connect it to the universal testing machine (UTM) MTS 810.

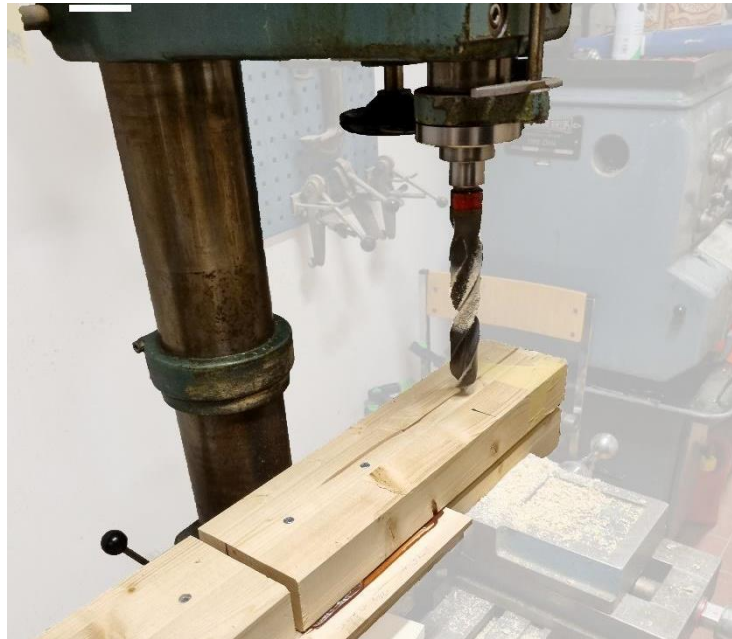


Figure 18 Drilling of one of the specimens.

2.2.2 Experimental procedure

After the specimens were prepared, they were tested using the MTS 810 universal testing machine, please refer to figure 20 on the following page. For the adhesive specimens, the loading head movement rate was set to 1.0 mm/min to account for their higher stiffness compared to the mechanically connected ones. The testing equipment included a base, clips, and hanging dowels, which were properly positioned and aligned. The testing apparatus was calibrated for accurate measurements.

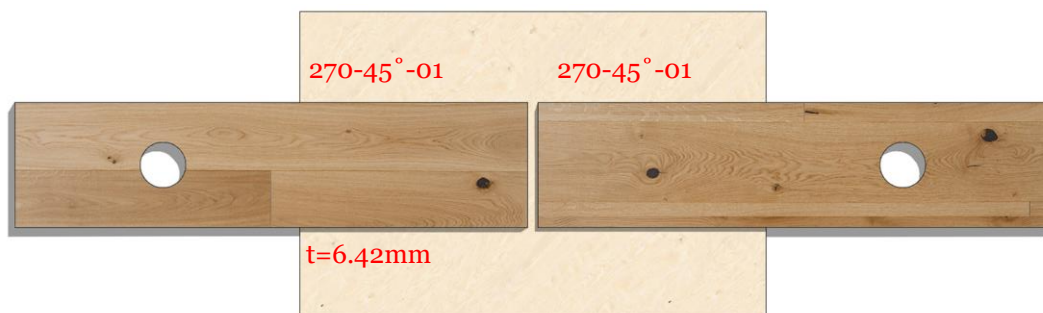


Figure 19 example of glued specimen with numbering.

Prior to commencing the test, all the distinctive characteristics of the specimens, such as width, grain angle, repetition number, and most significantly, the actual thickness of the plywood plate, particularly in the anticipated failure area located at the center of the specimen, were recorded on both sides, see figure 19 above showing the method used to write the data on the specimen.

To ensure proper contact between the specimen and the testing machine, an initial preload was applied. The testing machine was then started, and the live testing results, including the applied load and displacement data, were displayed on the screen. The test continued until the predefined failure criterion was reached.

During the test, the applied load and displacement data were continuously monitored and recorded. Subsequently, the collected data were used to calculate the desired parameters, including the net-tension capacity. The results were gathered and saved in a document under the name of the specific specimen, including details such as the width, grain angle, and repetition number.

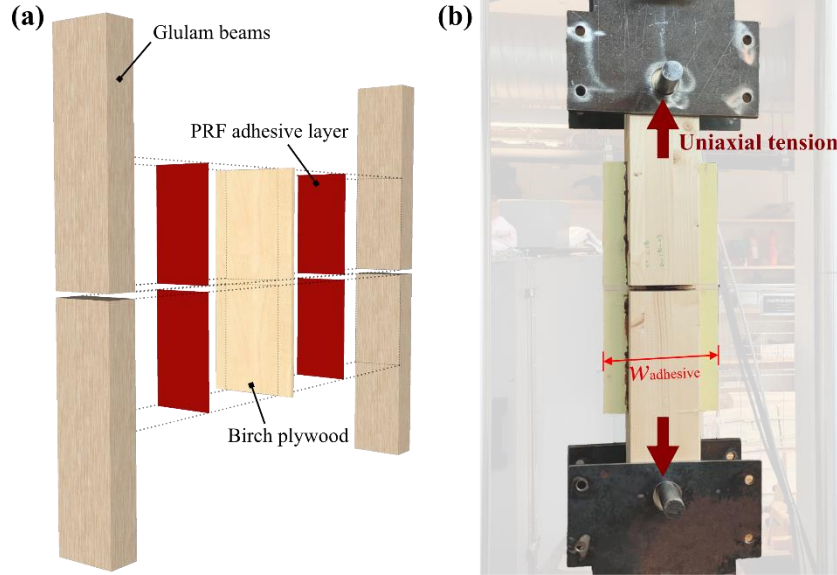


Figure 20 a) Specimen assembly process, and b) test picture of birch plywood specimens bonded with glulam beams via PRF adhesive.

2.3 Data analysis

In both the mechanical and adhesive test series, the ultimate load-bearing capacity R_u of each specimen was determined as the highest force recorded from the beginning of the test until the specimen's failure. This provides a measure of the maximum load the specimen can sustain before reaching failure.

For the plywood specimens, the tensile strength (f_t) was determined from the specimens with the lowest width (w) of 110 mm. The strength of each of the three repetitions of the 110 mm width was calculated, by using the equation:

$$f_t = \frac{F}{w \cdot t} \quad (2)$$

Subsequently, the mean strength of these repetitions was determined. Additionally, the mean thickness (t) of all the specimens was calculated. These data on strength and thickness are essential for building the analytical model.

2.4 Analytical model

After conducting all the tests and collecting the results from the repeated trials, a chart illustrating the mean results for each width was generated and plotted.

To develop an analytical prediction model, the concept of the spreading angles was used to calculate an effective width. The effective width (w_{eff}) was determined as the sum of the width of the connection area and the additional width on each side calculated using the equation $l \cdot \tan \alpha$ (l is the length of the connected region and α is the assumed spreading angle, see figure 21 below). The complete equation is presented below:

$$w_{eff} = w + 2 \cdot l \cdot \tan \alpha \quad (3)$$

Then an assumed force capacity (F_a) is calculated by using the calculated effective width for each angle, if the effective width is more than the actual width then the actual width is used. This can be represented in the equation:

$$F_a = f_t \cdot t \cdot w_{eff} \quad (4)$$

The analytical result then plotted for each spreading angle and width, then by using the R^2 method the analytical model that gives the closest predictions to the tested result is determined.

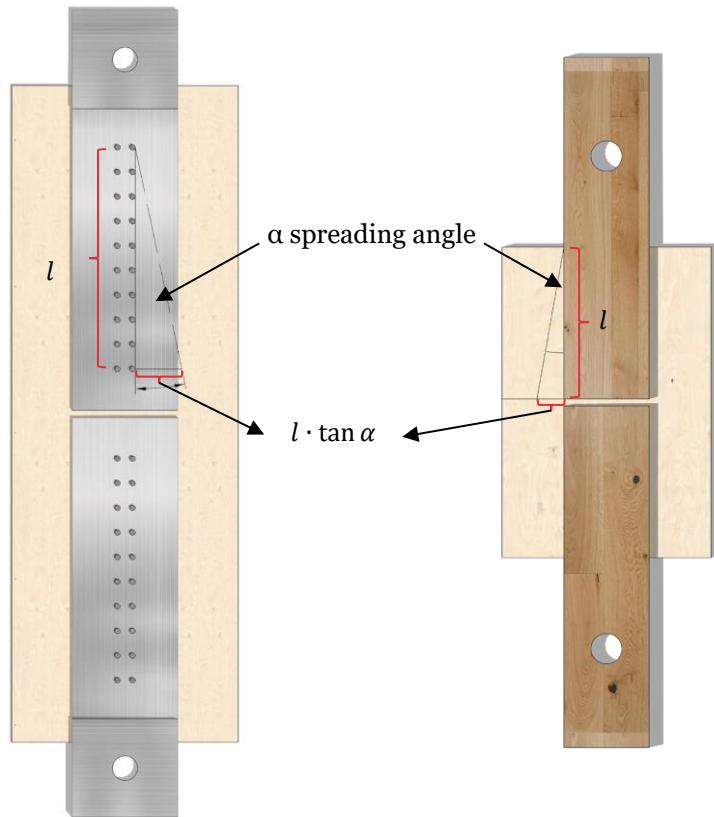


Figure 21 spreading angle, (a) mechanical specimen (b) glued specimen

3 Results

3.1 Plywood with mechanical connectors

3.1.1 Test results

The experimental tests were conducted on plywood connected with Mechanical connection via dowels at three different angles: 0, 22.5, and 45 degrees to the face grain. The net-tension capacity of birch plywood was investigated by varying the width of the specimens for each angle to the face grain.

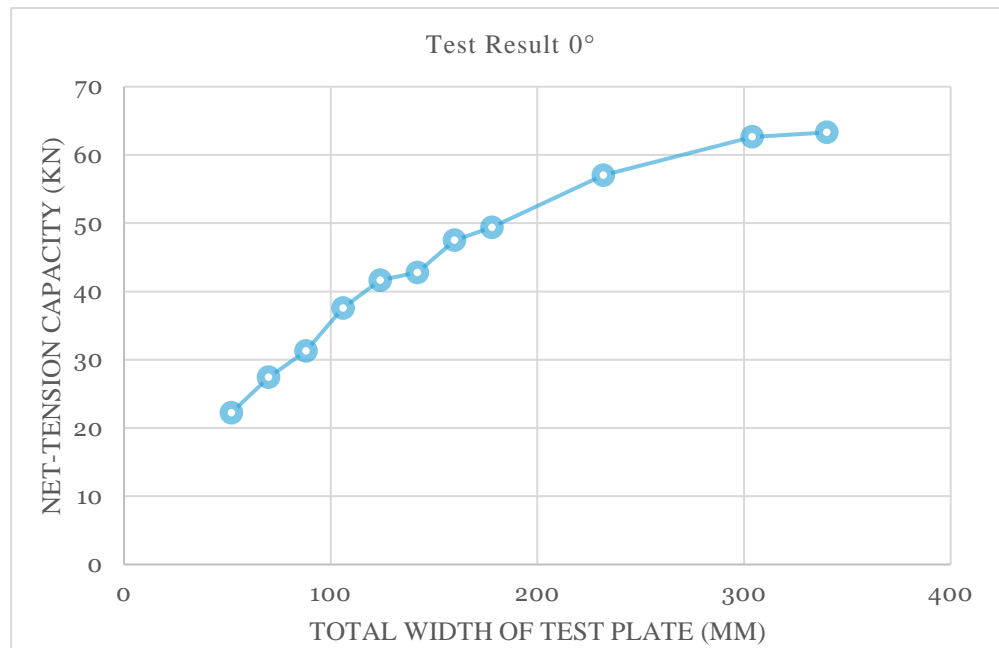


Figure 22 0-degree Net-Tension Capacity to Total Width.

As can be seen in Figure 22, a plateau was reached at 310 mm point and after that there is no big difference in capacity.

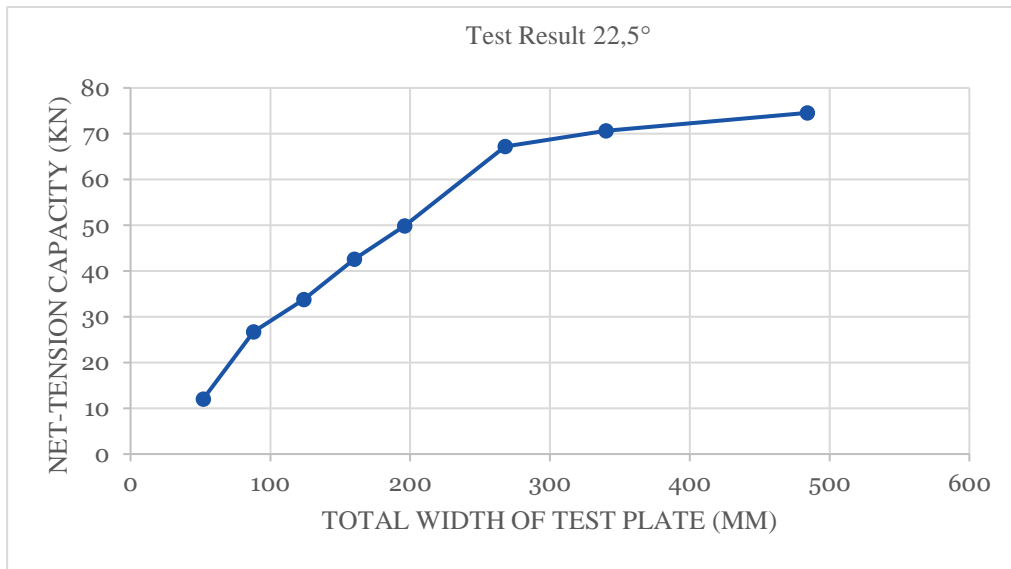


Figure 23 22.5-degrees Net-Tension Capacity to Total Width.

At an inclination angle of 22.5 degree, as shown in figure 23, the graph does not reach a definitive plateau; however, it is evident that it approaches the plateau, indicating that a few more tests would be sufficient to ascertain its exact value. Therefore, further studies are required to reach a definitive plateau. Additionally, an increase in the width of the specimens, do not accurately reflect real gusset plates used in timber structures. Another intriguing observation is that while the specimens at 0 degrees perform better with smaller widths compared to those at 22.5 degrees, the opposite holds true for wider widths. This unexpected phenomenon warrants further investigation to understand its underlying causes. This interesting result highlights the potential for future research to delve deeper into the reasons behind this phenomenon. It also emphasizes the importance of designing plywood gusset plates to ensure a consistent capacity across all inclination angles.

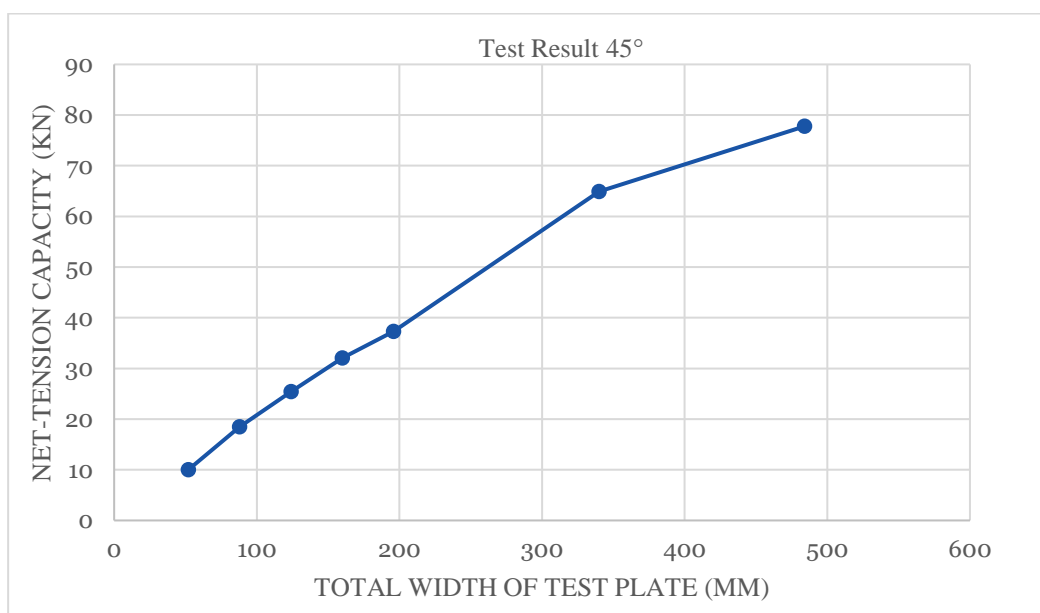


Figure 24 45-degrees Net-Tension Capacity to Total Width.

Test result for the 45 degrees is shown in figure 24. It didn't reach the plateau and we have to stop here unfortunately since it is out of the scope of this study. It needs more studies to determine the plateau. Again, it performs better than 0°degrees in wider widths.

3.1.2 Analytical predictions

Analytical predictions were carried out only for the plywood plates with the face grain angle parallel to the loading axis. This is due to that a plateau of the tensile capacity of birch plywood was only observed for the 0-degree specimens.

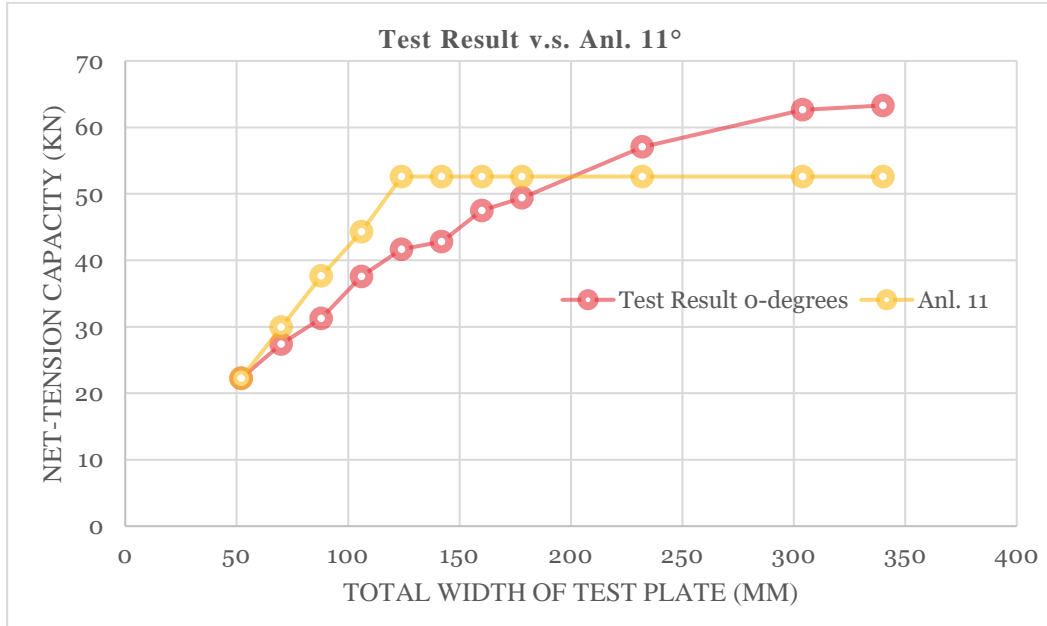


Figure 25 0-degree test result and its analytical prediction. $\alpha=11^\circ$ is closest spreading angle to the test result.

Following the completion of our calculations, it was determined that an inclination angle of 11 degrees ($\alpha = 11^\circ$) yielded the most accurate prediction in comparison to the experimental results, as depicted in Figure 25.

This finding highlights the effectiveness of the analytical approach in estimating the performance characteristics of glulam-adhesive-bonded plywood connections.

The coefficient of determination method (R^2) was employed to assess the precision of the analytical predictions and identify the closest match to the experimental data. Among the various inclination angles considered, the analytical prediction for $\alpha=11^\circ$ exhibited the highest R^2 -value of 0.7, indicating a relatively strong alignment with the test results. However, it is important to acknowledge the presence of certain deviations.

Notably, the capacities observed at narrower were lower than the prediction from the analytical model, while the capacities within the range of 200 mm to 340 mm exceeded the predicted values.

Despite these discrepancies, the analytical predictions obtained provide adequate grounds for drawing conclusions within the specified scope and objectives of our study. Nevertheless, further investigations are recommended to validate and improve the reliability of our findings.

Future research endeavors may explore additional parameters, including alternative joint configurations, variations in fastener types, or plywood properties, in order to obtain a more comprehensive understanding of mechanical connections between plywood and glulam.

The derived analytical predictions have practical implications for the design and implementation of plywood-glulam connections. They serve as a valuable tool for engineers and designers in making informed decisions regarding joint configurations, material selections, and structural performance. However, caution should be exercised, and the limitations of the analytical approach should be considered when applying these predictions in real-world scenarios.

In summary, although the analytical predictions exhibit certain deviations from the experimental results, they show promise in predicting the behavior of glulam-adhesive-bonded plywood connections. This study contributes to the existing body of knowledge and opens avenues for further research, ultimately advancing the understanding and design of these connections.

In summary, the analytical predictions, despite exhibiting deviations from the test results, demonstrate promise in predicting the behavior of plywood connected with glulam via mechanical connections. The findings of this study contribute to the existing knowledge base and open avenues for further research, ultimately advancing the understanding and design of these connections.

3.2 Plywood bonded with glulam via adhesive

3.2.1 Tests results

The experimental tests were conducted on plywood bonded with glulam via adhesive at three different angles: 0, 22.5, and 45 degrees to the face grain. The net-tension capacity of birch plywood was investigated by varying the width of the specimens for each angle.

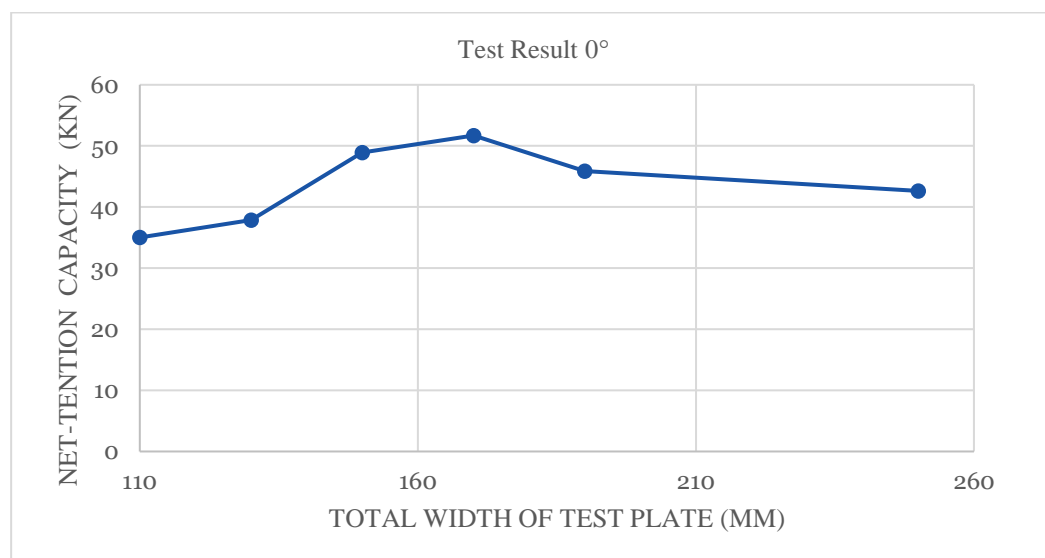


Figure 26 Test result for zero degrees to the face grain. A notable drop in capacity occurs after reaching the plateau.

At 0 degrees, the test results revealed an intriguing pattern. The capacity of the plywood initially increased with additional width until reaching a peak at 150 mm. Beyond this point, a drop in capacity was observed, as shown in Figure 26. This unexpected drop can be attributed to the presence of local fiber deviations within the middle part of the birch plywood plates, where tensile failure is likely to occur. These local fiber deviations arise due to the natural characteristics of plywood as a biological material made from birch, resulting in fibers that are not uniformly oriented in a single direction, as seen in figure 27.

Regarding the 22.5-degree inclination, the test results initially indicated a plateau in capacity after a width of 150 mm, see figure 28. However, upon further examination, it was observed that the capacity rose again beyond a width of 230 mm. Therefore, to precisely determine the plateau, additional tests beyond the scope of this study are warranted.

Nevertheless, it is important to note that plywood plates with widths exceeding 270 mm are seldom employed in structural applications. Thus, the tests conducted within this study provide valuable insights into the plateau phenomenon.



Figure 27 Local Fiber Deviation.

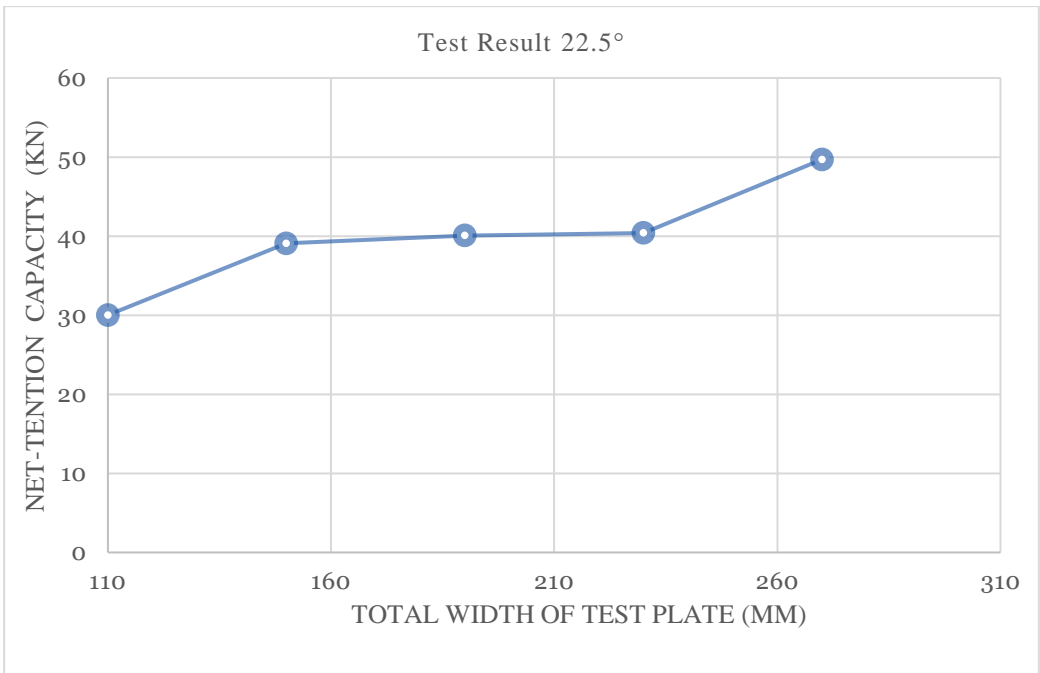


Figure 28 Test result for 22.5 degrees to the face grain. It shows a strange rise after the graph reach plateau. It needs some more result

For the 45-degree inclination, the test results displayed a gradual increase in capacity, gradually approaching the plateau. Although the plateau could not be conclusively determined within the limitations of this study, it is anticipated that conducting more tests would yield definitive results, please refer to figure 29.

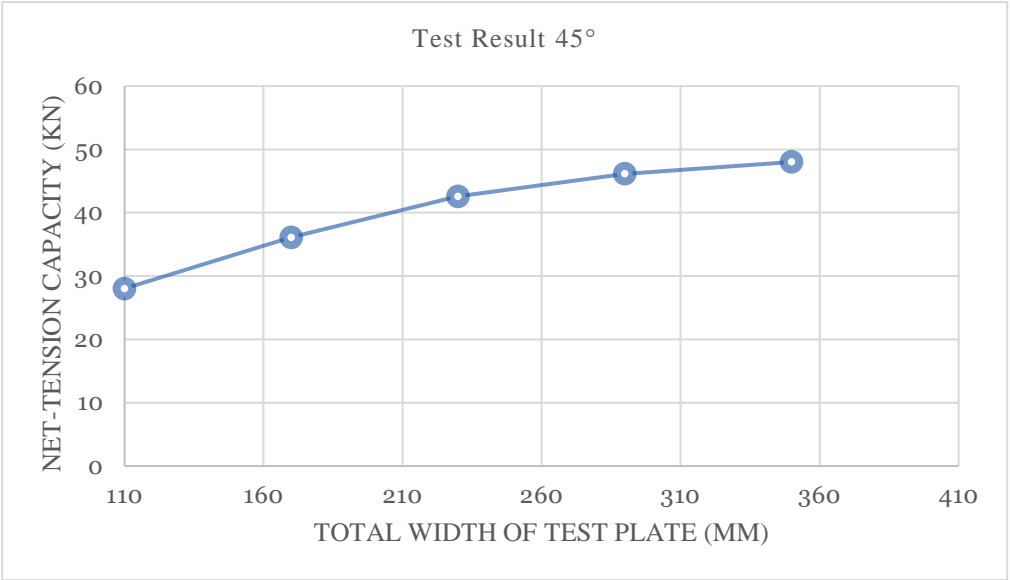


Figure 29 Test result for 45 degrees to the face grain. The graph demonstrates a consistent trend, with further tests required to determine the plateau.

3.2.2 Analytical predictions

Analytical predictions were only available for the 0-degree test results due to the absence of a plateau in the specimens tested at 22.5 and 45 degrees. Similar to the previous section, this limitation can be considered acceptable, given that wider plywood has to be tested and that kind of wide plywood plates are uncommon in timber connections.

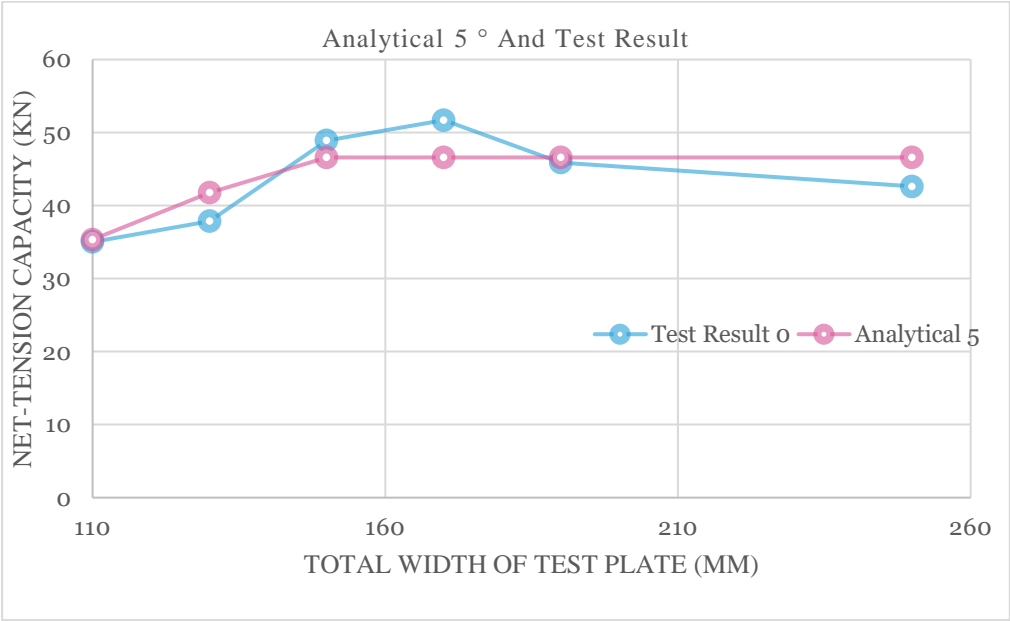


Figure 30 Plotted curves of both test- and analytical results five-degree variation.

Upon completing our calculations, we found that a spreading angle of 5 degrees ($\alpha = 5^\circ$) provided the closest prediction to the test results, as depicted in Figure 21. This finding suggests the effectiveness of the analytical approach in estimating the performance of plywood bonded with glulam via adhesive.

We employed the R^2 -Method to assess the accuracy of the analytical predictions and determine the closest match to the test results. Among the various spreading angles considered, the analytical prediction for $\alpha = 5^\circ$ exhibited the highest R^2 -value of 0.7, indicating a relatively close alignment with the test result. However, it is important to note that certain deviations were observed, see figure 30 on the previous page.

In particular, the capacity at smaller widths was lower than the predictions from the analytical models, while the capacity within the range of 150 to 190 mm exceeded the predicted values.

Despite these deviations, the results obtained from the analytical predictions are deemed adequate for drawing conclusions within the scope and objectives of our study. However, further investigations are recommended to validate and enhance the reliability of our findings. Future studies can explore additional parameters, such as variations in adhesive types, plywood properties, or alternative joint configurations, to provide a more comprehensive understanding of plywood-glulam adhesive connections.

The obtained analytical predictions hold practical implications for the design and implementation of plywood-glulam adhesive connections. They can serve as a valuable tool for engineers and designers in making informed decisions regarding joint configurations, material selections, and structural performance. However, it is important to exercise caution and consider the limitations of the analytical approach when applying these predictions in real-world scenarios.

In summary, the analytical predictions, despite exhibiting deviations from the test results, demonstrate promise in predicting the behavior of plywood bonded with glulam via adhesive connections. The findings of this study contribute to the existing knowledge base and open avenues for further research, ultimately advancing the understanding and design of these connections.

4 Conclusions

This study aimed to investigate the performance characteristics of plywood connections with both mechanical connectors and glulam adhesive bonding. Through experimental tests and analytical predictions, valuable insights have been gained, contributing to the understanding and design of these connections with plywood in timber structures.

In the case of plywood with mechanical connectors, the experimental results revealed a plateau is reached for 0 degree to the face grain. However, further tests beyond the scope of this study are necessary to precisely determine the plateau for 22.5- and 45-degrees angles to the face grain. Nevertheless, the findings provide important guidelines for structural applications of plywood.

The analytical predictions for mechanical connections exhibited deviations from the test results, yet demonstrated promise in estimating the behavior of these connections. While the predictions offer valuable insights within the study's scope, further investigations are recommended to enhance their reliability. Future research can explore additional parameters, such as alternative joint configurations, variations in fastener types, and plywood properties, to deepen our understanding of mechanical connections between plywood and glulam.

For plywood bonded with glulam via adhesive, the test results at different inclination angles provided important observations. The behavior at 0 degrees showed an unexpected drop in capacity after reaching a peak, attributed to local fiber deviations. The 22.5-degree inclination exhibited a potential plateau, but further tests are required to accurately determine it. The 45-degree inclination demonstrated a steady increase in capacity, approaching a plateau yet to be determined. Analytical predictions were only available for the 0-degree inclination, indicating the closest match to the test results.

The analytical predictions for adhesive-bonded connections also displayed deviations. While these deviations should be considered, the predictions offer valuable insights for the design and implementation of plywood-glulam adhesive connections. Caution should be exercised when applying these predictions in real-world scenarios, considering the limitations of the analytical approach.

Overall, this study contributes to the existing knowledge base, proving plywood could be a good replacement of steel gusset plate given the performance of plywood connections with mechanical connectors and glulam adhesive bonding. The results provide a foundation for engineers and designers to make informed decisions regarding using plywood, how to configure it and its structural performance. However, it is imperative to continue research efforts, validating and enhancing the reliability of the findings through further investigations.

In conclusion, this thesis provides valuable insights into the behavior of plywood connections with mechanical connectors and glulam adhesive bonding, paving the way for future research and advancements in the field of timber structures.

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