Effect of relative humidity and temperature on the strength properties of finger-jointed furniture components from solid scots pine

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Abstract

Mechanical strength in wood has always been compromised due to the complex behaviours of the material when interfered with moisture and heat. These factors has always limited the use of the material. However, the will of using more sustainable materials such as wood has contributed to a wider use of the material and several new ways that lead to improvement. Several of these methods emphasizes the joining of two wood components together endwise, where finger-joints are the most commonly used method. Several studies regarding how well finger-joints can withstand external load has been made over the years. However, many of these studies focuses on geometrical properties or strength varying in different species. This study focuses on how relative humidity and temperature affects mechanical strength in finger-jointed wood products. There were beliefs before the research started that increasing temperature would affect mechanical strength greatly. However, it turned out to only affect the mechanical strength marginally, and that relative humidity was the largest contributor to decreasing tolerance levels. It is important to notify that mechanical strength seemed to be directly affected to moisture content (MC), which is a result of an interactive relationship with both temperature and RH. It was particularly MC-levels above 9.2% that showed a decrease in mechanical strength. This research also focused on estimating the relative MOR per cross-section in varying conditions. This method could be used to better understand to which degree hygroscopic factors affects mechanical strength relative to the glued-surface area between finger-joints. Even though the findings in this study indicates that there seems to be possible to estimate strength in regards to relative MOR per cross-section, the results were not sufficient to be viewed as scientifically proof. The findings could however be used as ground for future studies.
Acknowledgement

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1. Introduction

The use of wood based products have always been an important part of human history. Throughout the centuries, wood has had several important fields of applications, such as fuel and building material, as well as for creation of essential tools. But due to the complex nature of the material, it has been fairly limited usage over the history. This is mostly due to the anisotropy, hygroscopicity and biodegradability of wood [15]. Besides, the properties of wood varies a lot among species, lumber, or even within a growth ring. Thus, it is very difficult to estimate the accurate strength and lifespan of such heterogeneous material. It led to use alternative materials such as steel, aluminium, plastics etc. whose mechanical strength are predictable. These materials are not renewable and however not favourable for a more sustainable future. A wider range of wood usage in different wood-based products could be a justifiable solution.

From the 20th century and forward great work has been done to improve the usage as well as the lifespan of wood-based products. Since the durability of wood always has been a problem for wider range of utilization, new technologies are emerging to enhance the durability of wood. Such technologies could focus on different preservation methods as well as wood refining. Even variations of the technological development has been taken place and are improved in the past century. The flexibility within the wood industries has thereafter increased [14]. One problem with commercial wood-based products is that they are rarely produced with wood material that is obtained from the same tree. The sizes of planks could vary depending on the size and characteristics of the trees. It is therefore necessary to produce the components needed from the specimen that is available, which could overcome the limit of wood material. Several methods has however been established to increase the utilization rate at production. Some of these methods focuses on the ability to join wood components together and therefore increases the utilization rate as well as the range of applications [11].

To have the option and ability of joining two wood components together endwise has been seen as a flexible alternative within the production line. This enables one to work with different lengths of components since they easily could be joined together with each other to get the desired length for different purposes. The most common way of joining wood components are however the use of finger-joints.

Fig. 1: The finger-joint method is one of the most preferable methods when joining two wood components together endwise.
One of the main purposes of the finger-joints is to simplify the selection of wood components to get the desired length. Nevertheless, it is also as much important to have a good understanding of how strong the actual bonding needs to be in order to satisfy the user. A solid piece of pine that is knot-free and has a relatively normal growth ring span has a modulus of rupture (MOR) of somewhere around 100 MPa [14]. This depends however on the characteristics of that specific material. However, finger-jointed wood components will always have lower mechanical strength than that of solid wood components even at most favourable conditions.

Since finger-jointed products are widely used within the industry and that the export of finger-jointed products are increasing, it raises the question if different environmental elements affects the mechanical strength as well. This is of course a very important aspect for the companies that uses domestic species in their production line.

Today there is a wide utilisation of finger-jointed wood components in the industries. The inclining slopes on each side of the fingers are the most recognizable trait of the finger-joint profile. These slopes could however vary in size and shape depending on different types of usage. The finger-joints are today seen as a standard method in the wood industry. This is due to a wide consideration that finger-joints are a reliable option in comparison to other methods used such as scarf joints [2].

The mechanical strength between two joined components is largely dependent on the geometrical design of the finger-joints [6]. There are several elements that has a direct effect on the geometry, were if one element is changed another is directly influenced. This is due to the interrelationship between the different elements of the finger-joints. The geometry may however have a strong correlation to the mechanical strength, but there are also various methods that arguably could have a great impact on the mechanical strength as well. Such a method could be the direction of the finger-joints. Usually, the finger-joints are located at locations that hardly exposes them for any pressure or stress. This is particularly true in the home furnishing industry were several components are used as covering panels or wooden beams that are not exposed particularly for any high levels of stress. Hence it is not often taken in consideration whether the finger-joints are placed horizontally or vertically (Figure 2). However if the main goal is to increase the mechanical strength, or at least, trying to understand the correlating factors affecting it, it is wise to notify how these two methods differs from each other, even though this study does not exactly focus on that particular factor.

Fig.2. Vertical (left) and horizontal (right) finger-joint.

The method of finger-jointed components are widely used in the furniture industry, especially at companies like IKEA of which this study is based on and sponsored by. Therefore it is
understandable that as much information regarding this method as possible is most the advantageous. Even though this method has been used in the IKEA range for quite some time, is not always equivalent with fewer quality issues in their production line.

One of the reasons behind this study is the sudden increase of defected finger-joints used in various components in the IKEA product range. This later leads to expensive recalls and gives the brand a bad reputation amongst customers. It is important for IKEA to emphasize that safety for the customers is vital and that the quality issues that could lead to severe damage to the customers has to be taken very seriously. The cracks that are occurring in the finger-joints has the ability to cause an incident that could lead the customer dissatisfaction with the appearance, and could in worst case may cause an injury.

It is important to clarify that the cracks are not always a safety issue. Many of the finger-joints that appear on the furniture have a bad adhesive work on them or has been exposed for poor workmanship. This might not affect the strengths or durability in the material in a major way, but this kind of poorly executed operations leads to a visually defected product and therefore cannot meet up to the customers’ expectations.

Since adding the adhesive and joining the wood components together endwise occurs before the components are assembled into the finished product, the production process eliminates the components that are poorly glued or not glued at all almost immediately in the process. That is why most of the recalls of the finger-joints comes from the customers when the furniture is assembled after the product has left the suppliers.

Since there are currently no practical economic alternatives to finger-joints, it is in IKEAs best interest to develop this process as far as possible and to eliminate distinguishable quality variations in the production.

1.1. Aim and objectives

The aim of this thesis is to understand the effects of relative humidity, temperature, moisture content and finger-joint assembly on the mechanical strength of Scots pine. To achieve the aim, specific objects are set to:

- Determine to which degree mechanical strength in finger-joints gets affected by differentiating temperatures and relative humidity.

- Establish a comparable method that estimates the mechanical strength (MOR) a component can withstand when considering the differing ratio between glued surface area and the cross-section area. This method shows how much stress a cross section can withstand ($\rho$) when considering the relative correlations between mechanical strength and glued surface area. This method is later evaluated where two specimens with varying glued surface area are compared.

- Determine if MOR per cross-section differs in varying temperatures and RH. This could be helpful to understand just exactly how much impact the hygroscopicity actually impacts the mechanical strength.
1.2. Affecting factors

In order to decide the setting parameters and the elements important in this study, it is vital to understand the fundamentals of how much of an impact the different surrounding factors could have on the mechanical strength. Therefore it is wise to recognize in what fields were there could be essential to identify these problems. To use the Ishikawa diagram, and his method of using the “Seven M’s” [3], could provide a helpful method to identify problematic areas regarding the quality issues.

According to Ishikawa, primary factors that has a direct link to various quality issues in the production line, and secondary factors that does not necessarily affect the quality in a direct way. But due to the lack of information alongside with poor education it could lead declining quality over time. Of course, since this study emphasizes on the mechanical properties of finger-jointed components, it is highly unlikely that most secondary factors could play a larger role in this study.

Primary factors could have a direct impact on the mechanical strength. The primary factors often has the possibility to be measured and to make conclusions based on those measurements. Some of these factors though have a larger impact on the result than others, but regarding to this research only a smaller portion of the factors are being considered, mostly those regarding materials and methods. The other factors however are also taking a part in the testing process but are not measured in a way that the study is dependent on. Those factors are:

- **Material**
  If the material being used is defected in any way it could cause a major impact on the finished product. The materials that primarily are being issued are such as wood components and adhesive. The characteristics that could affect the outcome is such as temperature and moisture content within the material. These aspects needs to be examined in more detail since there seems to be a strong correlation with the issues regarding this study. To specify what species of wood that is being tested on is also essential to retrieve a convincing end result, since mechanical properties varies amongst different species of wood.

- **Machine**
  Tool wear or old machines could have a negative impact on the quality of the finger-joints. Such faults could be due to vibrations, dirt or changing of temperatures. This is however not a factor that is going to be evaluated in this research, although the quality of the machines and the tools are being controlled before the making the specimens that are used in the tests. This is done by engineers from IKEA to make sure that chances to get specimens with distinguishable errors are as small as possible.

- **Methods**
  The methods that are used when working with finger-jointed products are essential to the end result. Different methods could for example include geometry of finger-joints, appliance and amount of the adhesive as well as specifications regarding pressure time and appliance time of the adhesive. All
of these methods are considered when performing the tests but at the same time is important to limit the study that a clear conclusion could be extracted from the end result.

Vertical finger-joints is another method that are debated amongst authors to have an impact on the mechanical strength as well. It is noted in a study from A. Roth [24] that vertical finger-joints increase the mechanical strength in bending tests. If this could be implemented on IKEA products it could be a simple way to minimize deflected finger-joints. Even though this does not necessarily fall in this study’s range is it wise to consider testing these factors in future studies.

- **Measurements**
  If the machines in the production line are incorrectly calibrated, it could lead to a larger amount of defected products and/or products with poor quality. It is fairly common that a redundant amount of adhesive could occur within two faulty measured components and lead to poorly executed components. This factor that is not included in this research, however engineers from IKEA participated in the production of the specimens, which will minimized the chances of faulty measurements.

On the contrary, secondary factors are more ambiguous than primary factors since they do not have the same direct impact on the end result. However, in some cases, it is possible that they actually could have effect on the end result. Since these factors are not measurable in the same way as the primarily factors, they are not considered in research work. The components that are used to finalize this study are also handpicked by the engineers from IKEA, which means that these components therefore has minimal influence by secondary factors.

- **Human errors**
  If the employees somehow misinterprets the routines or misinterprets the tasks given to them, this could lead to a large amount of distinguishable quality variations. Human errors are not being considered to be a vital part of this research even though the routines were controlled when the specimens were collected from the supplier.

- **Management**
  If management somehow have misinterpreted the guidelines and recommendations regarding expectations of the finger-joints, it is possible that wrong information has been presented to the employees and in the extension caused a quality issue. This is also something that this study is not primarily focusing on. But, it is recommended to have a small check in with the supervising manager just to get the idea of how things are being implemented.
Environment

Environmental disturbances could have a large negative impact on the production. Example of such could be change in temperature that could affect the drying time of the adhesive. Since wood is a hygroscopic material it has the ability to be influenced by the surrounding environments. Due to these physical properties, the environmental factors could have a large impact on the end result. Even though the purpose of this study is not regarding external environmental elements within the factory, it is necessary to measure both temperature and humidity in the facility in which the components are stored. This is also done by engineers from IKEA when it is time to collect the specimens for this study.

2. Theory

There are essentially five steps (5) that are particularly important when manufacturing finger-jointed wood products [11]. Variations of these five (5) steps could however occur differently depending on the system that is used, but it is important to point out how necessary these steps are when producing good joints.

The first step (1) is to select the material and to decide eventual preparations that are needed. Since no adhesive can bond as strong as solid wood, it is sufficient to choose material that has normal abnormalities to get as reliable result as possible. There are however recommendations of the high the level of Moisture Content (MC) needs to be in order to maximize bonding strength. This could of course vary between different adhesives, but most adhesives has the maximum bonding ability between 6% and 17% MC [11].

The second step (2) is the formation of the joint-profile. The most common method to create joint-profiles includes rotating cutting tools that are equipped with shaped saw blades, even though dies are also frequently used in the wood industries. Some of these tools are also assembled by smaller blades into one large tool, which makes it flexible to add the blades necessary to create a particular joint profile. Step three (3) emphasizes the importance of appliance of the adhesive, were there are several approaches available. A mechanical applicator is commonly installed in the production line, which simplifies the process. However, there are also more primitive method that implies the use of tissue paper soaked in adhesive as well [18]. These methods are not used as much in modern industries any longer though.

The fourth step (4) focuses on assembling the finger-jointed wood components where both the physical assembling of the components as well as pressure is regarded. The physical assembling usually occurs not to long after the components are freshly sawn and has had adhesive applied onto them. A steady amount of pressure is necessary to complete the joining between the wood components. The pressure needed is depending on the viscosity of the adhesive as well as the quality of fitting of the fingers. According to Pavlov [19] it requires a pressure between 3 to 6 kilograms per square centimetre (kg/cm²) at least in order to ensure maximum bonding strength.

Step five (5) regards the curing of the adhesive, which is considered to be the final step. Usually adhesive is cured at room temperatures (21°C) and above. The required time could however be reduced simply by adding heat to the curing process. Most systems today apply
some sort of supplying heat to the adhesive in order to increase the speed of production. However, adding of the extra heat could be performed before or after application of the adhesive [20]. On the contrary, if the adhesive are applied onto exceptionally wet material or if the material has low temperatures bonding strength could be sufficiently lower.

There have been several relevant studies conducted regarding the mechanical strength of finger-joints. Some are focused on different species of wood, trying to distinguish different traits of the different species that could affect the mechanical strength. Others are however, more focused on the adhesive or different geographical factors that could affect the mechanical strength. Even though this study is very specific and only considering a few factors, it is safe to say that many of the previous studies that has been made before has provided a lot of vital information to this study. According to author’s knowledge, no research has been conducted so far to find out the relative MOR per cross-section before. However, there are few studies that focused on geometrical characteristics of finger-joints. Studies by authors Prins [5] and Gong [6], showed that the tip thickness have a more complex way of transmitting stress in finger-joints. What these authors basically mean is that the tip thickness introduces severe changes in different sections of the finger-joint. This leads to stress concentrations that affect the expected load at breaking point. There are even some studies that have focused on finding a correlating ratio between different geometrical factors. In this contrast, Castro and Paganini [12] indicates that there is a correlation ratio between the width of the tip and the partition of the finger-joints. A deeper understanding on the mechanical strength in finger-joints within the industry would be possible if the present research objective is combine with the findings achieved by Castro and Paganini.

A few researches has also been conducted in regards to how the ambient temperature affect the mechanical strength. These studies concluded that different temperatures had an impact on the strength in finger-joints [7]. In addition, that research however used different adhesives in the testing process but could still provide essential information to this study as well.

2.1. Considered factors

It is well known that a larger glued area between the sliced components have a direct impact on the mechanical strength. This is due to a larger amount of friction in the finger-joints has a strong correlation to the contact area between two components [4]. This could be vital information when summarizing the important elements that affects the mechanical strength in finger-jointed wood products. However, there are several parameters that are considered to have a great impact on the mechanical strength were most of them are as mentioned primary factors. Listed below are elements that have been proven by authors of having a direct impact on the mechanical strength of finger-joints. Some however, has chosen not to be part of this study even though they are affecting the mechanical strength. This is due to the strive after as having as narrow spectrum of specimens as possible to get an easier and clearer estimation of what are the direct elements causing variations in the mechanical strength.

- **The length of the fingers**

It has been stated that the area in between the two pieces of wood components have a strong correlation between size and strength [1]. The length of the fingers is one way
to increase or decrease the glued area and hence test this theory. However, since it is relatively difficult to change tools in the middle of production, it is necessary to find other ways when evaluating MOR per cross-section. It is also difficult to find longer finger-joints with the same geometric design as shorter ones. This changes the level of stress that finger-joints can be exposed for, and should be avoided in this study.

- **Shoulder or no shoulder**
  It is fairly common that finger-jointed components access what is called a shoulder (Fig. 3). This is due to esthetical reasons since it is easier to get a clean cut when the components are sawn with a shoulder. Nevertheless, some finger-joints have their entire width covered with fingers as well. This increases the risk of crushed wood fibres since the tools are operating on smaller surfaces. However, the glued area increases in finger-joints without shoulder. This is therefore a perfect way to determine MOR per cross-section in varying specimens.

![With shoulder](image1.png) ![Without shoulder](image2.png)

Fig. 3: *Examples of finger-joints with and without shoulder. The increased area on the component without shoulder (right) becomes clearer.*

- **Geometry of the finger-joints**
  There are several terms regarding the geometry of the finger-joints, such as partition (also referred to as “pitch”), tip thickness and slope. These are all crucial to the mechanical strength, not only because they could increase the glued area and hence add conditional friction between the components, but also in a more complex way such as inner stress factors that occurs within the wood itself [6] [12]. Even though this is a critical factor that should be examined in the future, it is not prioritized in this research. There are however studies that examine the possibility of having a ratio between the tip and partition [12]. It is possible to examine the opportunity of combining both of these studies to find a universal method of estimating the mechanical strength of finger-joints in the future.
- **Amount of adhesive**
  The amount of adhesive being used is one of the many factors that has an impact of the mechanical strength in finger-joints. The appliance process is however well monitored by the suppliers and can therefore easily be investigated by engineers from IKEA. This particular factor is therefore not considered in this study.

- **The quality of the adhesive**
  Today, it is required that a D3-classified adhesive is used in the production of furniture for indoors. However, there are several different variations of adhesive, which works differently. Some examples are resorcinol resins, phenol-resorcinol resins or melamine resins [11]. All those adhesives have different capacities regarding temperature, colour or strengths (depending on the material of the components). This study is however strictly limited to a PVAC-based adhesive that fulfil the IKEA requirements and follow the specification that IKEA has issued. This will be provided by IKEA before the joining of the wood components occur at the suppliers, which means that this study will not focus on different variations of adhesive used since IKEA has strict guidelines on which adhesive to use.

- **Variation in temperature**
  Since finger-jointed wood components are used in countries with differing temperatures it is important to clarify how the temperature influences the mechanical strength. The variation of temperatures contributes to the hygroscopic characteristics of wood resulting in changes of the wood material. It is therefore highly recommended to include this variable in the study as well since the mechanical strength could be dependent on variation in temperatures. The best way to conduct these tests are to place specimens in climate chambers that are set to different temperatures and then test the mechanical strength afterwards.

- **Moisture content**
  The moisture content has a direct impact on the strengths of wood. The strength decreases relatively to the moisture content up to 30% and after that the mechanical strength is stable [15]. This relation is however for strengths in solid wood. Furthermore, there is a correlation between the moisture content in wood and the mechanical strength in the adhesive as well [13]. It is therefore wise to conduct tests that explores this theory. The humidity is also an important factor to take in consideration when testing mechanical strength. This is due to the hygroscopic properties of wood, which makes it highly dependent on the surrounding environments. Wood has the ability to gain liquid (absorption) and release liquid (desorption) to find the *equilibrium moisture content* relative to the air humidity [14]. These characteristics need to be taken in consideration when testing the specimens regarding the moisture content and relative humidity.
3. Materials and method

3.1. Material
The specimens are made from solid Scots pine (Pinus sylvestris L.) and have a cross-section of 32×40 mm (width × height) and the length 600 mm. This means that every component have the length about 311 mm each since the fingers overlaps each other. The specimens have a density of 580 kg/m³ and has a moisture content of 8%. They are also knot free and have a span of growth rings ranging from one (1) and two (2) mm between each other. The wood comes almost exclusively from either matures wood or sapwood, which excludes the possibility of extractives that exists in heartwood to interfere with the adhesive [13]. A total of 84 specimens needs to be conducted from Prawda in order to have a completely satisfying test result with a reliable medium value and a reasonable standard of deviation according to engineers from IKEA.

IKEA regularly uses adhesives that are rated as D3-standards, meant that the bonding strength is no less than 10 MPa after being stored in normal ambient conditions (20°C, 65% RH) for at least seven (7) days. However, the adhesive in this study is considered to be a polyvinyl acetate (PVAC) adhesive which is considered to be a thermoplastic adhesive. This makes the adhesive more sustainable when in contact with moisture and has therefore greater bonding ability that a regular D3-classified adhesive. The suppliers evaluates the bonding strength according to the EN 205:2009 [25] test standard which uses a tensile-shear test to measure bonding strength. The adhesive, which has the reference number 3311, was provided by Akzo Nobel. This particular adhesive is especially made for use in wood based products as well.
Following the ISO 20152-1:2010 [22] sufficient bonding was achieved at a temperature of 18°C. The 3311-adhesive is considered to have a mechanical bonding which means that the glue-molecules penetrates the wood pores and create a bonding when the adhesive hardens.
The assembling of the components was done at the supplier by engineers from IKEA.

3.2. Source of material
The material was collected from the Prawda-factory in Olecko, Poland. This research required an easily monitored, well-controlled and functional line of production to retrieve sufficient specimens. To meet these demands was it necessary to join the components manually to ensure sufficient quality and correct measuring (See Appendix, Picture 7). This also includes appliance of the glue onto the components as well though the glue was manually applied. It is important that the joining between the components occurs as soon as possible, but no later than 24 hours after machining to ensure maximum bonding strength in the finger-joints.

The components had already been freshly sawn in recommended sizes and with recommended geometrical properties when arrival at the Prawda factory. Before the joining process of the components could be performed, a measuring of different affecting elements had to be done in order to ensure the correct values for the specimens.
Table 1: The technical properties that was obtained during the joining of the wood components.

<table>
<thead>
<tr>
<th>Affecting elements</th>
<th>Technical data</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture content in material</td>
<td>Below 8%</td>
<td>This is regarded as a relatively low moisture content. [16]</td>
</tr>
<tr>
<td>Adhesive appliance time:</td>
<td>1-12 s.</td>
<td>The adhesive was applied manually by a small brush.</td>
</tr>
<tr>
<td>Pressure from the press:</td>
<td>4 kg/cm²</td>
<td>The pressure executed endwise onto every specimen.</td>
</tr>
<tr>
<td>Temperature of the adhesive:</td>
<td>18 °C</td>
<td>The temperature of the adhesive is estimated due to the temperature in the facility in which it was stored prior to the applying process.</td>
</tr>
<tr>
<td>Temperature of the material:</td>
<td>20 °C</td>
<td>The temperature of the wood components are estimated due to the temperature in the facility in which the joining process occurred.</td>
</tr>
<tr>
<td>Humidity in facility:</td>
<td>35%</td>
<td>This is estimated to be a relatively low humidity [16].</td>
</tr>
<tr>
<td>Temperature in the facility:</td>
<td>20 °C</td>
<td>The temperature in the facility was not affected in a large way by the outside temperature.</td>
</tr>
<tr>
<td>Pressure time:</td>
<td>55 to 65 s.</td>
<td>The pressure time was estimated to be kept around one minute.</td>
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</table>
The temperature in Olecko was -9°C which had a large impact on the specimen values even though the temperature inside the factory was significantly higher. This becomes clear when observing the relative humidity in the facility, which was measured to 35%. This is considered to be relatively low, even though a normal humidity-level is regarded to be in between 25% and 60% [16]. The temperature had most likely a large impact on the moisture content as well, which was measured to be below 8%. This is also regarded to be relatively low compared to the moisture content during normal conditions [16]. This is probably due to the hygroscopic correlation between the material of wood and its surroundings, which had a low humidity due to the lower temperatures.

3.3. Method
Since the components are joined together manually are there however, a larger risk to have defective specimens due to human errors. It is also likely that some distinguishable errors will occur in the bending process at the Test Lab as well. It is therefore, recommended to increase the amount of specimens to at least 100 pieces to have at least some extra specimens if some are compromised in the bending process. The bending test is going to be executed at IKEA-Test Lab in Álmhult, Sweden.

A total amount of eighty-six (86) specimens was conducted from Prawda, which were two (2) more than required to have a sufficient amount of specimens. Defected specimens were used when calibrating the Instron Uniaxial Testing Machine correctly. Defected specimens were sorted out based on the basis of twists, warps or poor adhesive work in the finger-joints (See Appendix, Picture 2). There are of course deflected specimens in the regular line of production as well, even though most of them are separated early on in the quality check. The specimens had originally a larger cross section area of 34×40 mm when retrieving them from the supplier. They were however planed later on in order to eliminate all uneven surfaces and redundant amounts of adhesive that occurred in the assembly process. The planing of the specimens were however executed in a traditional way that did not decrease the mechanical strength in a major way. This is due to controlling the process were the specimens were aligned in order to be exposed for minimum stress.

Basically, there are three (3) factors which are particularly important when estimating the geometry of the finger-joints. The length of the fingers (1), the partition (2) and the width of the tip (3). Since a change in geometry could increase or decrease the mechanical strength it is crucial to limit this research to one kind of geometric shape to get as a transparent and narrow result as possible. Due to a wide usage within the industry was the geometry used in this study decided alongside with technicians from the supplier to be as described in figure 4. The measurements are provided by LEUCO, a cutting tool manufacturer.
<table>
<thead>
<tr>
<th>Batch number</th>
<th>Climatic conditions</th>
<th>Temperature (°C)</th>
<th>Specimens</th>
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<td>Relative humidity (%)</td>
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<td>- With s.</td>
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<td>12</td>
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<td>- Without s.</td>
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<td>- Without s.</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>80</td>
<td>45</td>
<td>- With s.</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Without s.</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>50</td>
<td>23</td>
<td>- With s.</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Without s.</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td><strong>Total number</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>84</strong></td>
</tr>
</tbody>
</table>
The geometry of the finger-joints used in this study. All measurements are in mm.

The finger-joint length is measured from the base and had the length of 10.59 mm. This is considered as a reliable size that correctly reflects the sizes commonly used within the industry.

The distance between two finger-joints are referred as partition or pitch and is measured from the middle of one finger-joint to another. The partition is depending on the joint-degree angle (also referred to as slope angle) and the width of the tip since there are a correlating relationship between these elements. In this particular case the partition was 3.8 mm and the joint-degree angle was 7°.

The width of the shoulders were 3 and 3.4 mm. Since the amount of fingers are a correlating interplay of having or not having a shoulder, it is also wise to notify that the number of fingers, in an indirect way, also are a part of this study as well. Since the definition of “shoulder” is easier to comprehend and easier to measure it is the most preferable factor to use to evaluate the purpose of this study.

It has been widely discussed amongst scientists that the finger-joint tip thickness has a large importance on the mechanical strength. It has been concluded that the strength increases with the thinner tip, hence most authors recommend that one keep the tip as thin as practically possible [8] [9] [10]. This research has the tip thickness set to 0.6 mm.

Since different test methods retrieves varying magnitudes of load depending on the used method, it is important to recognize what mechanical properties that are most valuable to this research. Therefore, it is wise that the used test method should present a result that explicitly shows the mechanical properties of finger-jointed wood products. For wood, there are generally four types of mechanical strength that are measured-tensional, compression, shear and bending. The most common method is however a static bending test, where the material is horizontally placed on top of two metal support bars whilst the load is applied mid span onto the material. This method is the preferred test method of this study as well since a bending test fairly reflects the reality of how load is presented onto the finger-jointed wood components in the furniture industries.
To obtain scientifically valid results, it is necessary to have sufficient amount of test replications. This can keep the amount of specimens at a relevant level since using the “factor-by-factor” testing method [3] could lead to unfavourable amount of unnecessary tests. This study has focused on establishing a wide spectrum in the testing process by focusing on extreme high to low levels in RH and temperatures. With this logic, it is possible to set a reliable framework of how different RH-levels and the temperature affect the mechanical strength. Alongside with the extreme levels of RH and temperature, there are also control specimens at 50 % RH and 23°C of temperature to compare the results with in order to benchmark the results with normal conditions. These values are regarded to be standard at IKEA test lab and a good reference point regarding the conditions of the specimens. It is important to notify that another global standard is according to SS-EN 408:2010+A1:2012 set to be 20°C and 65% RH [17].

The anisotropic characteristics of wood allows the dimensions of the material to increase or decrease in different directions due to swelling when exposed for moisture. This is due to the cellular structures of the wood itself, which also varies between different specimens as well. It is therefore particularly important to notify these characteristics when the specimen are executed for higher humidity in the climate chambers. If the grains of the two joined components are positioned in a way, such as perpendicularly located growth rings, that favours a disproportional swelling it is possible that the end result could be affected. Since it is significantly more difficult to analyse and measure this procedure before the tests start, is it therefore wise to analyse any eventual distinguishable errors that occurs in the testing process after the bending test is executed. It is possible that any abnormalities could be explained due to unusually significant swelling of the material.

3.2 Bending test
It was redeemed necessary to make a 3D-model of the specimens in order to calculate the glued surface area down to the 100th millimetre. The model was created in SolidWorks and was based on blueprints from the tool manufacturer (figure 4). The measurements was however also controlled by engineers from IKEA by using a digital Vernier caliper with an accuracy of 0.05 mm to confirm that the measurements from the blueprints were correct.
Fig. 5: Specification of specimens with and without shoulder to calculate the glued surface area. Notify that the 32 mm depth is not shown in the figure.

Table 3: The cross section area of the specimens. The cross section is the same for both the specimens with and without shoulder.

<table>
<thead>
<tr>
<th>Cross section area</th>
<th>Numeric (mm)</th>
<th>Area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base*height</td>
<td>32 × 40</td>
<td>1280</td>
</tr>
</tbody>
</table>

Table 4: Glued surface area of specimens with shoulders.

<table>
<thead>
<tr>
<th>With shoulder</th>
<th>Numeric (mm)</th>
<th>Area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder width₁ × depth</td>
<td>3 × 32</td>
<td>96</td>
</tr>
<tr>
<td>Shoulder width₂ × depth</td>
<td>3.4 × 32</td>
<td>108.8</td>
</tr>
<tr>
<td>Slope length × amount × depth</td>
<td>10.67 × 18 × 32</td>
<td>6145.92</td>
</tr>
<tr>
<td>Tip width × amount × depth</td>
<td>0.6 × 17 × 32</td>
<td>326.4</td>
</tr>
</tbody>
</table>

**Total area:** 6677.12
Table 5: Glued surface area of specimens without shoulders.

<table>
<thead>
<tr>
<th>Without shoulder</th>
<th>Numeric (mm)</th>
<th>Area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>End slope₁ length*depth</td>
<td>4.1 × 32</td>
<td>131.2</td>
</tr>
<tr>
<td>End slope₂ length*depth</td>
<td>7.39 × 32</td>
<td>236.48</td>
</tr>
<tr>
<td>Slope length<em>amount</em>depth</td>
<td>10.67 × 20 × 32</td>
<td>6828.8</td>
</tr>
<tr>
<td>Tip width<em>amount</em>depth</td>
<td>0.6 × 21 × 32</td>
<td>403.2</td>
</tr>
<tr>
<td><strong>Total area:</strong></td>
<td></td>
<td><strong>7599.68</strong></td>
</tr>
</tbody>
</table>

These values could later be used to evaluate the correlation between glued surface area and cross section in different environments.

It is important to establish a clear and simple method to compare and comprehend vital information. As discussed earlier in this study is comparing the relative MOR per cross-section used to find a correlation between glued surface area and mechanical strength. The reason why this method is used is to easily compare the mechanical strength between different sized components. A method that estimates the relative MOR per cross-section could therefore be applied in regards to all different sizes and different geometrical properties as well to get a well-proportioned estimation. This is possible due the relative relationship between the cross section area and glued surface area, as well as the relative MOR for one particular specimen.

Area difference-ratio, denoted by

\[ \delta_1 = \frac{\text{Glued surface area} \_1 (\text{mm}^2)}{\text{Cross section area} \_1 (\text{mm}^2)} \]  

(Eq. 1)

*Fig. 6:* Glued surface area (left) and Cross section area (right). It is the size difference (ratio) between these two areas that important to reach some of this study’s goals.
The equation used to calculate the MOR (MPa) in a 3-point bending test is as follows:

\[ \text{MOR}_1 = \frac{P L}{(b h^2)} \]  

\( P \) = the applied force in Newton (N).
\( L \) = span (length between points of support in mm).
\( b \) = the width of the cross-section (mm).
\( h \) = the height of the cross-section (mm).

As mentioned earlier in this study there is a strong belief that the glued surface area contributes to the increase of tolerance in the finger-joints. To show that any correlations actually occurs between these two elements it is wise to demonstrate how much stress a cross section is able to withstand relative to the glued surface area (See step 3). Since the stress is believed to be higher in specimens with a larger glued area, it is wise to show the relative correlation between these two factors alongside with specimens with shoulder. By using step 3 it is possible to get a good estimation on how much stress a cross section is able to contribute with, and since the cross section are the same for both specimens they therefore should have the same mechanical strength in regards to the cross section.

It is thereafter possible to estimate what size the glued surface area should be in order to reach the desired stress-level. The geometrical properties could be applied thereafter to provide the required glued surface area.

\[ \text{Modulus of Rupture (MPa) per area-ratio} (\delta_1), \text{ denoted by} \quad \rho_1 = \frac{\text{MOR}_1}{\delta_1} \]  

The calculations in equation 3 enables an estimation of how much stress one cross section is able to withstand.

3.3 Mechanical test

When the specimens arrived at the IKEA-Test Lab, they were immediately placed in a controlled climate to become fully acclimatized. This was accomplished within in a sealed room for 14 days with a temperature of 23°C and a relative humidity of 50%. The intention of this process was to get equal conditions for all specimens before the testing started to exclude that any thermal or hydrodynamic factors could influence the results.

The specimens were thereafter placed inside climate chambers to acquire the desired hygroscopic values. A few specimens were however considered to be control specimens and were only tested in their acclimatized environmental state, which was 50 % RH and 23°C. These specimens had the exact same dimensions as the ones being placed inside climate chambers. This procedure was necessary to get a good estimated benchmarking regarding to normal values when the results were presented.
A specific batch number was given each group of specimens that were exposed for every different climate. This made it easier to keep track on which specimens that had been tested and to notify the outcome (Table 2).

The specimens were also marked with their batch number and with a specific secondary number as well in order to more easily monitor the process. The batch number was simply based on which batch they belonged to, and the secondary number is ranging from 1 to 12. Specimens with shoulder were marked with numbers between one (1) and six (6), and specimens without shoulders were marked with numbers between seven (7) and twelve (12) (Picture 3).

Since there were only two climate chambers fully functional at the time, the batches had to overlap one another. This means that two (2) out of six (6) batches were exposed to the desired climate at any given moment. The estimated time for the specimens to reach the desired values were estimated to be between one (1) to two (2) weeks depending on which climate they were exposed to.

There was simply no exact answer on how much time that was deemed necessary to complete this procedure. This is mostly due to the complex nature of the material and the matter of fact that all specimen differs from one another. Lower temperatures and a lower RH is estimated to take longer time though. Therefore was continuously measuring the moisture content essential to estimate the time that was deemed necessary. However, the specimens used in this study spend 14 days inside climate chambers in order to retrieve the desired values. The 3-point bending test occurred however continuously and made it possible to analyse test results at the same time as batches were stored inside the climate chambers. This saved some time when processing the results of the tests.

To confirm that the specimens has reached the desired values within the climate chambers was it useful to measure the moisture content of the specimen. This is possible due to the hygroscopic nature of the material and that wood is constantly seeking its equilibrium moisture content [14].

To perform the 3-point flexural bending test, the specimens were placed between two span meanwhile the load was applied mid-span (Picture 4). This research is entirely focused on horizontal finger-joints since it has been studies that indicate that vertical finger-joints have greater mechanical strength than horizontal [11]. The distance between the span was 500 mm according to the ISO-10983:2014 standard [21]. The load and deflection of the specimen were recorded via computer, which specified the exact amount of force needed to reach specimen failure. The supporting span had rounded off bearing plates to reduce that any stress occurred from shearing could affect the result (Picture 5). Load was applied at 6 mm/s where the complete failure was achieved in no less than 30 s.

To test whether there were any significant differences between the bending strength value of with and without shoulder, a Student’s two-tailed group t test (at 95% level of significance) was performed using Excel 2016 program (Microsoft, Redmond, USA). To determine the effects of relative humidity on MOR, ANOVA was performed. A Duncan post-hoc test was carried when the differences in the treatment were more evident. The statistical analyses were performed using IBM® SPSS® Statistics, Version 23 (IBM Corporation, NY, USA). The significance level was set at 0.05.
4. Results

The results presented in the table below shows the mean values for both specimens with and without shoulders. It is particularly the applied load as well as MOR that are presented, alongside with the relative MOR per cross-section. The table also presents the level of significance between specimens with and without shoulder to compare if there are correlations between glued surface area and mechanical strength (See Calculations).

The batch that showed the highest value was batch 5, were specimen without shoulder had an MOR above 50 MPa. On the contrary, batch 2 showed the lowest values were both specimen with and without shoulders has values below 30 MPa. The specimen without shoulder showed an increase in strength between 8 and 55%.

Batch 1, 3, 5 and 7 also showed the highest values in MOE. The values ranged between 12 and 20% higher. These batches were exposed for lower MC than the other.

There were three batches that showed significant difference between strength between specimen with shoulder and specimen without shoulder, namely batch 3, 5 and 7.

Table 6: Bending strength and strength per-area ratio of different test material at various conditions. The values in parentheses are standard deviations.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Load (N)</th>
<th>MOR (MPa)</th>
<th>MOE (MPa)</th>
<th>MOR cross section (MPa)</th>
<th>Significance (P&lt;0.05)</th>
<th>MC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Batch 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(15°C, 30% RH)</td>
<td>With s.</td>
<td>2522 (263)</td>
<td>36.7 (3.8)</td>
<td>9325 (1389)</td>
<td>7.04</td>
<td>0.17 NS</td>
</tr>
<tr>
<td></td>
<td>Without s.</td>
<td>2721 (581)</td>
<td>39.6 (8.3)</td>
<td>9380 (1043)</td>
<td>6.68</td>
<td></td>
</tr>
<tr>
<td>Batch 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(15°C, 80% RH)</td>
<td>With s.</td>
<td>2109 (186)</td>
<td>29.5 (2.8)</td>
<td>7521 (338)</td>
<td>5.65</td>
<td>0.06 NS</td>
</tr>
<tr>
<td></td>
<td>Without s.</td>
<td>1949 (385)</td>
<td>27.2 (5.4)</td>
<td>6890 (905)</td>
<td>4.58</td>
<td></td>
</tr>
<tr>
<td>Batch 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(30°C, 30% RH)</td>
<td>With s.</td>
<td>2491 (296)</td>
<td>36.3 (4.2)</td>
<td>8813 (568)</td>
<td>6.95</td>
<td>0.00*</td>
</tr>
<tr>
<td></td>
<td>Without s.</td>
<td>3146 (295)</td>
<td>45.7 (4.3)</td>
<td>9219 (523)</td>
<td>7.69</td>
<td></td>
</tr>
<tr>
<td>Batch 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(30°C, 80% RH)</td>
<td>With s.</td>
<td>1692 (255)</td>
<td>23.5 (3.4)</td>
<td>6908 (943)</td>
<td>4.51</td>
<td>0.09 NS</td>
</tr>
<tr>
<td></td>
<td>Without s.</td>
<td>2077 (457)</td>
<td>29.0 (6.4)</td>
<td>7174 (514)</td>
<td>4.89</td>
<td></td>
</tr>
<tr>
<td>Batch 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(45°C, 30% RH)</td>
<td>With s.</td>
<td>2360 (298)</td>
<td>34.6 (4.3)</td>
<td>8415 (526)</td>
<td>6.63</td>
<td>0.01 *</td>
</tr>
<tr>
<td></td>
<td>Without s.</td>
<td>3652 (771)</td>
<td>53.9 (11.4)</td>
<td>10023 (971)</td>
<td>9.07</td>
<td></td>
</tr>
<tr>
<td>Batch 6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(45°C, 80% RH)</td>
<td>With s.</td>
<td>2395 (226)</td>
<td>33.4 (3.2)</td>
<td>7922 (820)</td>
<td>6.40</td>
<td>0.46 NS</td>
</tr>
<tr>
<td></td>
<td>Without s.</td>
<td>2399 (141)</td>
<td>33.6 (2.1)</td>
<td>8301 (589)</td>
<td>5.65</td>
<td></td>
</tr>
<tr>
<td>Batch 7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(23°C, 50% RH)</td>
<td>With s.</td>
<td>2579 (506)</td>
<td>37.4 (7.2)</td>
<td>10830 (692)</td>
<td>7.24</td>
<td>0.03 *</td>
</tr>
<tr>
<td></td>
<td>Without s.</td>
<td>3073 (544)</td>
<td>44.6 (7.9)</td>
<td>8831 (719)</td>
<td>7.58</td>
<td></td>
</tr>
</tbody>
</table>

1= Shoulder. *= Significant difference at the 0.01 level (Two tailed); NS: Non-significant.
5. Discussion

According to this study’s framework there are essentially two factors that needs to be examined in more detail to conclude any proof from the eventual findings. How mechanical strength differs in varying conditions (1), and if the relative MOR per cross-section is consistent throughout these varying conditions (2). To find out that there truly are differentials in mechanical strength between variations in temperature is a significance test performed on the received data to find eventual correlations. The goals that focused on finding a method that estimates the relative MOR per cross-section turned out to lack these scientific depth and could only be viewed as contribution to the previous theory. However, the findings in this research regarding the relative MOR per cross-section could be the framework for future studies.

The easiest and most comprehensible way to summarize the findings is to review the temperature and RH separately. When doing so it is possible to conclude any eventual correlations between mechanical strength. The tolerance was estimated to differentiate between temperature and RH, but the degree of which it differentiated was uncertain. It was therefore difficult to evaluate on beforehand how large the impact would be. Both specimens with and without shoulders were tested in order to receive results from different profiled components.

When analysing the mechanical strength in differentiating RH and temperature, it becomes clear that mechanical strength decreases more drastically when RH were increased. In order to make sense of these findings it is wise to acknowledge that moisture content (MC) is a value that is directly affected due to the relationship between RH and temperature. The MC is far more sensitive in regards to changes in RH and is greatly affected even by smaller variations [23]. On the contrary, mechanical strength were only marginally affected in regards to temperature in comparison to RH. However, the MC is greater when RH-levels are high and temperatures are low. This interrelationship between RH and temperature shows a clear correlation between increase in MC and the amount of mechanical strength finger-joints are able to withstand. The findings in this study shows that the tolerance-levels of the finger-joints are directly affected by this interrelationship, and thus weaker with increasing MC.

However, if compared to the control batch, the mechanical strength is not negatively affected between RH-levels of 30% and 50%, which is equivalent to a MC between 6 and 9% (marginally depending on temperature). This indicates that there are an absence of linear correlation between mechanical strength and MC between certain bound limitations. There seems though that the mechanical strength dramatically decreases somewhere between 9.2 and 14.7% (Between 50 and 80% RH), but the exact limit of when most decrease occurs is uncertain. It would be interesting if future studies could evaluate the critical MC-limit that are most destructive to finger-joints by using the findings in this study.

Previous study shows that the bending strength of finger joints is not significantly reduced at elevated temperature (20°C to 140°C) tested on different glue types [28]. In this study, it was also found that bending strength of finger joints was not affected by temperature significantly for all type pf samples except of those conditioned at 80% RH (Table 7 and 8). In addition, the higher bending strength at elevated temperature could be due to the lower MC of samples. However, it seemed that relative humidity played an important role for the reduction of bending strengths.
Table 7: Effect of temperature on MOR (MPa) in samples with shoulder at different relative humidity (RH) levels.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>30% RH</th>
<th>80% RH</th>
</tr>
</thead>
<tbody>
<tr>
<td>15°C</td>
<td>36.72 NS</td>
<td>29.50a</td>
</tr>
<tr>
<td>30°C</td>
<td>36.26 NS</td>
<td>24.59b</td>
</tr>
<tr>
<td>45°C</td>
<td>34.57 NS</td>
<td>33.39c</td>
</tr>
</tbody>
</table>

Mean values followed by different letter within a column indicate that there is a significant difference (P ≤ 0.05) as determined by ANOVA and Duncan’s multiple range test; NS = Non-significant.

Table 8: Effect of temperature on MOR (MPa) in samples without shoulder at different relative humidity (RH) levels.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>30% RH</th>
<th>80% RH</th>
</tr>
</thead>
<tbody>
<tr>
<td>15°C</td>
<td>39.63 NS</td>
<td>28.93 NS</td>
</tr>
<tr>
<td>30°C</td>
<td>45.68 NS</td>
<td>31.04 NS</td>
</tr>
<tr>
<td>45°C</td>
<td>49.89 NS</td>
<td>33.55 NS</td>
</tr>
</tbody>
</table>

Mean values followed by different letter within a column indicate that there is a significant difference (P ≤ 0.05) as determined by ANOVA and Duncan’s multiple range test; NS = Non-significant.

In order to find the effect of RH, bending strengths were compared using two-tailed t-test at two different humidity levels viz. 30% and 80%. Tables 9 and 10 show that samples acclimatized at higher RH humidity had lower bending strength and those differences were statistically significant. Which meant that MCs of samples are the biggest contributor to decrease the mechanical strength. To make sense of this result it is necessary to review the results from batch 5, which showed particularly high values. A highly likely reason for these higher values in batch 5 could be the slightly lower MC that occurs in batches that have higher temperature. Even batch 6 showed higher values than anticipated. However, it is not surprising that batches executed for higher temperatures, and hence lower levels of MC, can withstand greater stress since findings made in this study has shown that decreasing MC contributes to higher tolerance of stress in the finger-joints, which is in agreement with previous findings [28].
Table 9: Effect of relative humidity (RH) on MOR in samples with shoulder at different temperature levels.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>MOR (MPa)</th>
<th>Significant value (P&lt;0.05)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30% RH</td>
<td>80% RH</td>
</tr>
<tr>
<td>15°C</td>
<td>36.72</td>
<td>29.50</td>
</tr>
<tr>
<td>30°C</td>
<td>36.26</td>
<td>24.59</td>
</tr>
<tr>
<td>45°C</td>
<td>34.57</td>
<td>33.39</td>
</tr>
</tbody>
</table>

* Significant difference at the 0.05 level (two tailed) within rows; NS: non-significant.

Table 10: Effect of relative humidity (RH) on MOR in samples without shoulder at different temperature levels.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>MOR (MPa)</th>
<th>Significant value (P&lt;0.05)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30% RH</td>
<td>80% RH</td>
</tr>
<tr>
<td>15°C</td>
<td>39.63</td>
<td>28.93</td>
</tr>
<tr>
<td>30°C</td>
<td>45.68</td>
<td>31.04</td>
</tr>
<tr>
<td>45°C</td>
<td>49.89</td>
<td>33.55</td>
</tr>
</tbody>
</table>

* Significant difference at the 0.05 level (two tailed) within rows.

There are several reasons why the finger-joints could be so affected by MC. First of all, the adhesive is more exposed to moisture and could therefore get reduced bonding abilities. It is of course well known that moisture affects bonding strength in adhesives, but the magnitude of how much disturbance moisture actually could achieve was not well documented. The anisotropic behaviour of wood could also be a strong contributor for weaker mechanical strength. This becomes clearer when analysing single specimens that has had unexpected breakages very early in the testing process, were the unproportioned swelling at the specimen becomes more obvious. These shifts in the dimensions compromises the bonding strength in the adhesive and thus the specimen becomes weaker. The specimens in this research showed a dimensional increase between 3 and 4% for batches exposed for 80% RH. Variation of temperatures did not cause dimensional changes.

There are of course several factors that also could have a large effect on the mechanical strength aside from temperature and RH. The most relevant factor is as mentioned the geometrical properties that the joint profile possesses. However, this study excluded these geometrical properties from the testing process, even though studies indicates they greatly affects the mechanical strength. It is therefore important to mention that mechanical strength most likely differs between different geometric profiles, and that future studies could examine if any mutual correlation could be discovered.

Another factor that could affect the result was the method used to reach failure in the specimens. This research chose a 3-point bending test in order to evaluate the mechanical strength. A 4-point bending test could also be used to perform the same procedures, which highlights any potential deflects over a larger length span. However, by using a 3-point bending test it is possible to isolate any specific levels of stress on a material, and thereby get reliable results for testing finger-joints [26].

As well as determining if RH and temperature affected mechanical strength is establishing the relative MOR per cross-section between glued-surface area and mechanical strength also
a vital part of this research. Even though the results was not as scientifically significant, it may however be ground for theories and information for future studies.

The MOR per cross section is as mentioned estimated due to the relative strength between glued surface area and the cross section, where similarities between specimens with varying glued-surface areas are compared in order to ensure correlation between them. Before the mechanical tests occurred, there were a strong theoretical belief that there was a correlation between the glued surface area and the mechanical strength in finger joints. However, these theories were based on several per-reviewed studies, hence any eventual correlations were not unexpected and not ground-breaking for this particular study [4]. On the contrary, this peer-reviewed study was not considering the same comparison between MOR per cross-section. Besides, the impact on how much interference hygroscopic factors actually do to the adhesive were not part of previous studies, and therefore was any eventual presumptions only hypothetical. In order to compare how these correlations differs in variating abiotic conditions were a new method created in order to measure similarities between specimens with varying glued surface area.

What became clear after several batches had been tested was that this MOR per cross-section did not show any correlation between specimens in several cases. It was in particular batch 2 and batch 6 that showed no significant difference between specimens. However, there are several batches that shows a clear similarity between glued surface area and mechanical strength as well. This indicates that there indeed are reasons to continue researching these correlations.

What is interesting is that the control samples showed a clear correlation between glued surface area and mechanical strength. Results were as previously expectations very accurate were values ranged from 37.44 MPa for specimens with shoulders to 44.58 MPa for specimens without shoulders. The standard deviations from these tests were around 8 MPa, which is considered to be reliable. However, this correlation were not obvious when analysing the results from batches with very high or very low values of both temperatures and RH. This could indicate that variations of both temperature and RH affects the mechanical strength significantly more than the glued surface area does. It is therefore a possibility that estimation due to the MOR per cross-section is less reliable in extreme temperatures and especially in extreme humidity due to the unpredicted nature of wood-based material. This becomes more abundant when analysing the result of the batches themselves.

The results received from Batch 2 were rather unexpected were specimens without shoulders achieved lower tolerances than specimens with shoulders. When reviewing the result, this is in direct opposition of this study’s theory though specimen without shoulder should be able to withstand higher levels of stress. However, it is necessary to analyse both the standard deviation alongside with minimum values in order to find sense to this unexpected result.

First of all, the lowest value from the specimens without shoulder was 18.59 MPa. Compared to the second lowest at 26.57 MPa and the fact that the medium value is 27 MPa, it becomes clear that one specimen in particular was indeed responsible for the relatively low medium value. When analysing this abnormally weak specimen, it becomes clear that bad adhesive work is the cause of this unusually low tolerance level (picture 8). It is also highly likely that these diversification could occur more frequently when the material is exposed for higher amounts of moisture though the adhesives bonding strength could be compromised.

Even though geometrical properties are absent in this research does the geometric profile play a large role in the process. It is particularly the distribution of stress that occurs in the joints that distributes differently depending on if the specimen have a shoulder or not. This study chose to equip specimen with or without shoulders to elaborate eventual correlations between
glued surface area and mechanical strength. Even though this method has provided a reliable theory it is wise to consider variations in other elements in order to elaborate with these correlations. One of the reasons why this should be considered is that geometrical factors have a large interplay between the specimens used in this study (Figure 7).

![Image](image_url)

**Fig. 7:** The distribution of stress in specimens with shoulder (left) and without shoulder (right). The stress is at its greatest in the red area.

It becomes clear that the stress becomes well-distributed across the joint profile in samples without shoulder, and less well in specimens with shoulders. According to several authors are thicker finger tips less efficient to distribute stress where great stress concentrations could occur in narrow spots [8] [9] [10]. Even though the geometric profiles are the same for both specimens it is possible that the distribution of stress becomes less efficient and that the concentration of stress compromises the test-results. These greater stress concentrations could occur in specimens that possess shoulders since these specific joint-profiles exhibit the same geometric traits that thick fingers do. Therefore, it is wise to consider alternative ways to evaluate this theory in the future, where variations in width would be most preferred. Even though most findings in this study turned out to align with previous expectations, there were observations during the testing process that diverged from what was expected beforehand. If only analysing the final MOR and amount of load applied onto the specimen, no major abnormalities were discovered. What diverged from expectations though was how the specimen behaved when being executed to load and how the deformation pattern was presented. However, these deviations only occurred to the specimens that possessed higher MC and was particularly clear in specimens equipped with shoulders (Figure 9).

Solid wood panels made from Scots pine (*Pinus sylvestris* L.) has commonly an abrupt breakage when being executed in a 3-point bending test [15]. Even though the material possesses some elasticity the break usually fairly abrupt. This behaviour is true for most finger-jointed wood components used in this study as well (Figure 8). However, there was several specimens that diverged from this pattern. The abrupt break occurred on all specimens in 30% RH and in all temperatures, just the same as solid wood. This indicates that these specimens possesses as high stiffness as needed to have an abrupt breakage. The specimens exposed for 80% RH showed however a slight change in behaviour when being executed to pressure, particularly for specimens with shoulders, though there was a lack of abrupt breakage in the 3-point bending test (Figure 9). These variations became clearer after an increase in temperature and increase in RH, and was the most distinct in 30°C and 80%
RH. These abnormalities could be discarded as bad adhesive work, but the retrieved MOR-values from these tests were not particularly low as they would have been if the adhesive was poorly applied. Besides, since the specimens without shoulder were stored in the same climate and did not behave the same it is more likely that geometrical properties played a larger role.

Geometrical properties are known to have impact on the mechanical strength of finger joints in past researches [9] [10]. Even though this research stayed consistent with one single geometric profile was an interference with the end result almost inevitable. The abnormal behaviours that the specimens with shoulder possess could occur due to the transition of stress in the joint profile. It is therefore possible that the shoulder causes stress concentrations and will not permit stress to distribute evenly throughout the joint profile. This could cause the finger-joint to yield at a slower pace and therefore lacks an abrupt break.

![Stress-strain curve showing abrupt failure. These particular values are taken from specimens without shoulders from batch 6 (45°C, 30 RH).](image1)

![Stress-strain curve showing abrupt failure for specimens with shoulder. These values are taken from Batch 4, (30°C, 80 RH).](image2)

However, these slower breakages became more apparent between temperatures at 15 to 30°C and the relative humidity at 80%. At higher temperatures, the break once again becomes more
abrupt and the finger-joints more stiff. Since MC-levers are higher in lower temperatures it is realistically a strong contributor to this lack of elasticity. When analysing the Modulus of Elasticity (MOE) it becomes clearer that a significant decrease could be found in specimens exposed for higher RH and lower temperatures. A low MOE could be responsible for this deviating breakage though low MOE-values indicates that the material lacks stiffness [27]. On the other hand was the lack in stiffness more abundant in specimen that was equipped with a shoulder. This indicates that geometrical properties could indeed play a larger role in these deviating MOE-values. As mentioned are the distribution of stress occurring differently depending on if the specimen are equipped with or without shoulders. It is therefore a possibility that an increase in MC (and therefore a decrease in MOE) as well as having geometrical input could affect the breakage behaviours of the specimens. Even though this study does not examine this particular factor it is still a big part of the behaviour of the material and should therefore not be excluded entirely.
6. Conclusions
This research has by following this framework conducted several important findings that could contribute to improvements in the production line in the future. All findings in this study was controlled by ANOVA and Duncan multiple range tests in order to ensure that the results indeed were reliable.

1. Relative humidity (RH) affects mechanical strength in finger-joints with a decrease in tolerance up to 55% in high values.

2. Differentiating temperatures has no significant impact on mechanical strength in finger joints.

3. The mechanical strength is stable between 30% and 50% RH (6 to 9.2% MC, marginally depending on temperature). However, values above 50% RH (9.2% MC) shows a decrease in tolerance. The exact threshold above 50% were the mechanical strength decreases the most is still uncertain.

During the evaluation of this study has several findings been determined to have solid scientific relevance (See 1, 2 and 3). A few on the other hand did not reach that high level of scientific certainty and hence no proof was established (4, 5, 6 and 7). However, these findings contributes strongly to the previously thought theory and could therefore be used as ground in future studies.

4. There seems to be a correlation between the MOR per cross-section and the differencing area and glued surface area.

5. The impact that glued surface area has on mechanical strength becomes less reliable with increasing RH and temperature. There are thought that abiotic elements disturbs the mechanical strength more than what glued surface area does.

6. The distribution of stress occurs differently depending on if the specimen are equipped with or without shoulders.

7. Modulus of elasticity in finger-joints seems to decrease when MC increases. If low MC is combined with the certain geometrical properties does it results in low stiffness and a lack of abrupt breakage.
7. References


8. Appendix

Picture 1: The manually operated press used to assemble the specimens. The required pressure was achieved due to hydraulics.

Picture 2: Finger-joint where too much glue has been used in assembly. Therefore, a fully accomplished merged was not achieved.
Every batch had twelve specimens, where every specimen was marked with a batch number (1-7) accompanied with a secondary number, specifying if the specimen was equipped with or without shoulder (1 – 12).

The load was applied mid-span onto the finger-joint profile.
Picture 5: The rounded off metal plates are used to minimize damage onto the material as well as minimizing any eventual shearing stress to compromise the result.

Picture 6: The machine used in this study was a INSTRON uniaxial testing machine that could apply loads up to 100 Kn.
To fully control all parameters in the assembly process it is necessary to assemble the specimens in a manually operated press.

Picture 8: When the adhesive has accomplished a successful bonding are there more crushed fibers left in the joint profile (right).
Picture 9: Climate Test Systems AB provides climate chambers with plenty of room for the specimens used in this research.
9. Calculations

The control specimens were the first ones to be tested in the INTRON uniaxial testing machine. This is to get a good estimation of what values to expect later in the study.

Batch 7

Table 11: Shows the test results for specimens with shoulder from batch no. 7.

<table>
<thead>
<tr>
<th>Specimen label (No.)</th>
<th>Maximum load (N)</th>
<th>Estimated MOR (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.1</td>
<td>2451.68</td>
<td>35.69</td>
</tr>
<tr>
<td>7.2</td>
<td>2045.42</td>
<td>29.72</td>
</tr>
<tr>
<td>7.3</td>
<td>2827.55</td>
<td>40.88</td>
</tr>
<tr>
<td>7.4</td>
<td>3091.79</td>
<td>44.92</td>
</tr>
<tr>
<td>7.5</td>
<td>1960.31</td>
<td>28.63</td>
</tr>
<tr>
<td>7.6</td>
<td>3099.41</td>
<td>44.81</td>
</tr>
</tbody>
</table>

Mean: 2579.36, 37.44

Standard deviation: 505.82, 7.25

Minimum: 1960.31, 28.63

Maximum: 3099.41, 44.92

Table 12: Shows the test results for specimens without shoulder from batch no. 7.

<table>
<thead>
<tr>
<th>Specimen label (No.)</th>
<th>Maximum load (N)</th>
<th>Estimated MOR (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.7</td>
<td>3771.46</td>
<td>54.80</td>
</tr>
<tr>
<td>7.8</td>
<td>2833.58</td>
<td>41.38</td>
</tr>
<tr>
<td>7.9</td>
<td>2806.33</td>
<td>40.78</td>
</tr>
<tr>
<td>7.10</td>
<td>3511.25</td>
<td>50.77</td>
</tr>
<tr>
<td>7.11</td>
<td>2272.82</td>
<td>32.86</td>
</tr>
<tr>
<td>7.12</td>
<td>3242.58</td>
<td>46.88</td>
</tr>
</tbody>
</table>

Mean: 3073.01, 44.58

Standard deviation: 543.58, 7.87

Minimum: 2272.82, 32.86

Maximum: 3771.46, 54.80
The correlation between the cross section and the glued area surface can be estimated first after the load and stress for the specimens are known. To retrieve the information needed are the mean values used in the calculations.

**With shoulder**

\[
\frac{6677.12}{1280} = 5.2165 \ (\delta_1). \quad (1)
\]

\[
\frac{1.5 \times 2579.36 \times 500}{32 \times (40^2)} = 37.78 \text{ MPa (MOR}_1) \quad (2)
\]

\[
\frac{37.78}{5.2165} = 7.24 \text{ MPa (} \rho_1 \text{).} \quad (3)
\]

**Without shoulder**

\[
\frac{7599.68}{1280} = 5.93725 \ (\delta_2). \quad (1)
\]

\[
\frac{1.5 \times 3073.01 \times 500}{32 \times (40^2)} = 44.58 \text{ MPa (MOR}_2). \quad (2)
\]

\[
\frac{45.01}{5.93725} = 7.58 \text{ MPa (} \rho_2 \text{).} \quad (3)
\]