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CROSSLAM - TODAY'S USE AND IMPLEMENTATION OF NEW WOOD SPECIES

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CROSSLAM - TODAY’S USE AND IMPLEMENTATION OF NEW WOOD SPECIES

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Abstract

The building industry in Sweden is dominated by concrete today. However, this material has a greater impact on carbon emissions compared to wood. By examining some of the general properties of wood and specifically cross laminated timber we have explored the basic advantages and disadvantages of this relatively new and mildly used building material, as well as, investigated why it has not developed to be a favored building material in the industry. After reviewing interviews with a manufacturer, a structural engineer, and a contractor, inexperience seems to be the main reason for this.

Some properties of the different wood species used in the dissertation has been presented as well as properties of crosslam elements

We have also presented how the Gamma-method can be used as a simplification to evaluate stiffness according to Eurocode 5.

A parametric study has also been conducted. Seeing that there are other species of wood with a higher rolling shear modulus than spruce it makes sense testing one of those in crosslam elements. From a designing point of view the parametric study shows that it is hardly worth switching to previously unused wood species in crosslam, at least in spans of 4 and 8 m, gaining 14% in moment of inertia at most.

As a second part of the dissertation we have tested Poplar, Birch, Hybrid Aspen, and Spruce in regard to mechanical properties. The main objective has been to understand how the rolling shear affects structural design of crosslam elements. The rolling shear strength is often the limiting factor together with the outermost layers ability to withhold traction forces in crosslam. The experiments together with the parametric study is the base of the second part of the dissertation.

Preface

The dissertation is the final part of our bachelor degree of science in engineering at Lund University. The dissertation comprises 22.5 credits and the work has been carried out at the Department of Construction Sciences and in cooperation with Sweco AB.

There are a lot of people that have been very helpful. However there are a few people we especially want to thank. Agne Helmö, whose initiative got the project started and who also manufactured the test specimens with great precision. Our two supervisors, Dr. Henrik Danielsson and Dr. Peter Persson, who have helped us with all we have asked for, at all times. Professor Erik Serrano, who has been committed to make this report as good as possible. Mikael Andersson, and the rest of the group at Sweco, who have made us feel at home in their office. Svenskt trä, who has provided literature and graphics. Arthur Grabowski and Dr. Jessica Dahlström, who helped us to run the MTS-machine and last but not least we want to thank Daniel Wilded, Jens Erik Jörgensen and Christopher Rosman for the fruitful interviews.

Helsingborg in May 2018

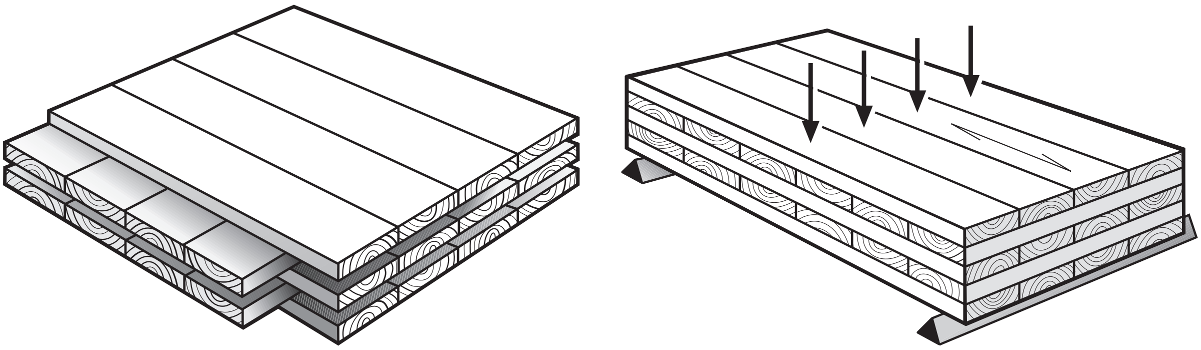
Dejan Reluskovski and Axel Stolt

Contents

1. Introduction

1.1 Background

Cross laminated timber, CLT, crosslam and X-lam are the names of a building material made by glued wooden boards with every layer placed perpendicular in relation to each other. Crosslam, which is often considered the correct term together with X-lam, is produced with an odd number of layers and in general has one of the two in-plane directions which is stiffer than the other. As a building material crosslam has been around since the early 2000s. Wooden buildings higher than two floors were prohibited until the year 1994 in Sweden. When new regulations with function-based rules were announced, new wooden-based materials were introduced [1].



(a) (b)

Figure 1.1:

Crosslam is mostly used in loadbearing structures such as floor structures and walls. One of the benefits of crosslam panels is the possibility to make large prefabricated elements that are easy to assemble on site. Because it is a large massive wooden element, it is also easy to perforate for doors, windows and other installations. Another benefit is the environmental aspect of using a wood-based material. The prefabricated elements are lighter than the same prefabricated structures in concrete which means less CO_2 emissions during transports. In addition, crosslam also provides CO_2-sequestration possibilities. Crosslam elements can be used to extract energy by burning them when the structure has fulfilled its purpose. Elements could also potentially be re-used if handled correctly during the lifespan of the building. Other benefits include high airtightness and the possibility to realize longer spans than typically possible using more traditional wooden structures.

Crosslam is traditionally made of spruce. The implementation of other wood species such as birch, hybrid aspen and poplar could provide some insight on new fields of applications of crosslam products.

Since 2018 "The Swan"(Svanen) certified crosslam-elements can be found on the Swedish market[2].

1.2 Purpose

There are two main purposes of the project. The first is to look into crosslam today; how it is used, what the main advantages and disadvantages are and current challenges for further increased use of crosslam in the building industry. To fulfill the purpose we can formulate the following research question: Why is wood not used to the same extent as concrete [3]?

The second purpose of the project is to investigate the possibility to use other wood species than spruce in the different layers of the material. The wood species that have been studied are Poplar, Birch and Hybrid Aspen. To fulfill the purpose we can formulate the following research question: Is it beneficial to use one of these wood species over Spruce for crosslam?

1.3 Method

The first part of the project was conducted trough a literature study. To complement that, interviews were held with people with good insight in the use of crosslam today.

The second part consists of experimental tests and a parametric study. Test specimens with different compositions of wood species were tested. The literature study covers properties of different wood species regarding strength and stiffness in different directions and regarding general suitability and general advantages and disadvantages.

1.4 Limitations

In the second part of the project, only the bond line strength strength with respect to shear (rolling shear) has been tested. There are other properties of the new cross-sections compositions which are relevant but these are not included in the dissertation.

2. Crosslam today

Crosslam, or wood in general, is not used to the same extent as concrete in Sweden today. In order to find out why, a number of different actors in the building industry have been asked to give their thoughts about the subject.

2.1 The manufacturer's perspective

An interview has been held with the Production Manager at Martinson group, Daniel Wilded [4], with 14 years of experience of crosslam. Martinson group is the largest manufacturer of crosslam in Sweden. They manufacture roughly 22,000 m^3 per year. There are a number of new manufacturers expanding to the Swedish market e.g. Stora Enso, Södra and Setra. Daniel welcomes this even if they are competitors. He thinks it is good since Martinson themself can not supply the demand of crosslam in Sweden today. He also points out that the other manufacturers sell the building material while Martinsons sells an overall concept with drawings, calculations, and material.

When Wilded was asked what he thinks is the biggest bottleneck for the use of crosslam in Sweden, he thinks it is the contractors. The client listens to the contractors and if they do not show confidence in crosslam less clients will choose the material. He believes that the architects and the structural engineers have good knowledge ,but, a big problem with the structural engineers in Sweden is that they do not take responsibility for their work with crosslam. They usually write a disclaimer something along the lines of "assembled according to the manufacturer's instructions". This defeats the whole purpose with a structural engineer and forces Martinsons to do the same work again .

It is hard to determine a specific cost of crosslam per m^3 since it depends on several factors such as thickness, number of layers, width, length etc. However, according to Wilded the price of crosslam/wood is roughly the same as concrete , with the same strength, in large parts of Sweden. There is a slight difference in the southernmost parts of Sweden since there is more competition with concrete manufacturers from northern Europe.

Wilded also points out that many contractors only look at the price of the material itself which he thinks is a mistake. To make a fair comparison speed of assembly, crane costs and costs for piling, for example, should be taken into account. One last factor he points out is the lack of competence which by itself leads to a higher cost when the contractors see the use of crosslam as a risk.

2.2 The engineer's perspective

Christopher Rosman [5] is a structural engineer at Sweco Structures AB in Jönköping. He has worked in projects where crosslam has been used. Rosman does not think it is more difficult to work with crosslam than other building materials, you just have to think more on the detailed design. He mentions moisture, acoustics, fire and stiffness in connections as examples. He says that the initiative to use crosslam varies. Sometimes the client wants it and puts it as a requirement, sometimes Rosman recommends it.

Rosman thinks there are a number of advantages with using crosslam. It is light, which is usually an advantage. However, when constructing tall buildings it can be hard to handle the lifting forces. The delivery times for crosslam is relatively short in comparison to prefabricated concrete elements. It is a natural and renewable material.

Rosman was asked what he thinks is the biggest bottleneck for the use of crosslam today. He thinks the lack of experience is a big factor. When there is not enough experience the price goes up and a higher price makes less clients use the material. He also mentions that it would facilitate his job if there were standardized solutions for details from manufacturers. These kind of solutions take a lot of time.

2.3 The contractor's perspective

The contractors point of view is represented by Jens Erik Jörgensen [6] who is a Group Manager at Skanska Teknik. He has good insight of Skanska's work with crosslam. Skanska has some experience of work with crosslam but not very extensive. Jörgensen explains that they have been a bit restrictive with wooden buildings since they have some bad experiences of working with wood. The biggest problem Skanska has had is related to moisture. The constructions have not been properly protected against the weather during assembly which has led to problems later on.

When Jörgensen is asked what he thinks is the most important reason for a small number of projects with wooden structures in Sweden today he states several. One big problem is the lack of experience. There is not enough competent personnel with the knowledge of how to build efficiently in wood. The lack of experience leads to higher cost during assembly but also a risk of warranty issues related to moisture later on. Jörgensen also says that the amount of structural engineers that have experience of work with wood is very limited. The final thing he mentions is that when people want to work with wood or crosslam they choose a structural system that is designed to be built in steel or concrete and want to redesign it to be built in wood which he thinks is a bad way to go.

Lastly, Jörgensen thinks that there will be more wooden buildings in the future. If properly planned and executed, a wooden building will be cheaper according to Jörgensen. There are also large environmental benefits with wooden buildings compared to steel and concrete.

3. Wood properties

The chapter covers the material properties of wood in a general manner. It provides information about wood in areas such as mechanical properties, fire, acoustics, heat, moisture, and cost.

3.1 Strength and stiffness properties

Wood is an anisotropic material [7], which means that it has different properties in different directions. There are three different directions in which the properties varies (see Fig 3.1). Longitudinal, which is the same direction as the wood grain. Radial, which is perpendicular both the grain and the annual rings of the wood. Tangential, which is perpendicular the grain and parallel the annual rings. There are significant differences in, mainly the material strength and stiffness between the different directions, but also other properties such as moisture, diffusivity and creep. The strength and stiffness of the wood species tested in the dissertation are presented in Table 3.1. There is a lack of data in literature regarding the material properties of other wood species than Spruce.

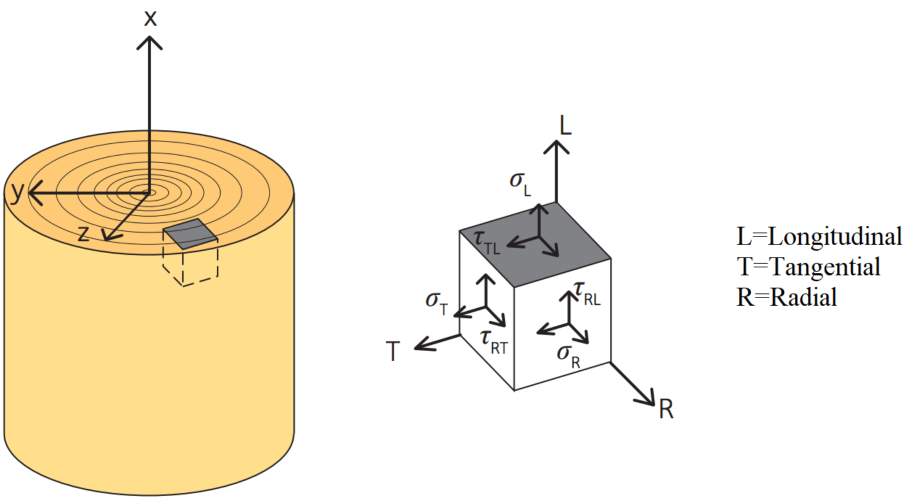


Figure 3.1: The different directions of wood.

Table 3.1: Material properties of wood [8] [9] [10] [11] [12] [13] [14].

Properties	Spruce	Birch	Poplar	Aspen
Strength [MPa]				
Flexural strength	75	115	70	75
Compression strength parallel the grain	40	57	38	42
Compression strength perpendicular the grain	7	10	3.4	2.6
Shear strength	9.5	12	8.2	5.9
Stiffness [MPa]				
Modulus of elaticity	11,000	11,000	10,900	11,000
Rolling shear modulus	50	175	127	
Density [kg/m^3]				
Mean density	420	550	420	380

3.2 Fire resistance

If an untreated board of wood is exposed to fire, it will ignite. The burning process will continue inwards at a somewhat constant speed. However, this is a slow process thanks to the carbon layer that is formed by the fire on the surface of the wood. Inside the carbon layer there is a unaffected part of the cross-section. That unaffected part of the cross-section must be designed to carry the whole load in the event of fire. This is an advantage compared to e.g. steel that must be protected by something else than the material itself. The carbon layer is a good insulator that makes wood relatively resistant to fire which in turn means that protective cladding is not always needed. Wood insulates well against heat. This means that during a fire most of the heat that is transferred between areas is through diffusion or fire gases [15].

Crosslam has mainly the same properties as normal wood but with some significant differences. These differences are due to the composition of the cross-section with layers of wood and glue. There is currently no method of calculation for crosslam for fire in SS-EN 1995-1-2. When designing crosslam for fire, there is a method for calculating the effective cross-section in "Fire Safety in Timber Buildings". The method in "Fire Safety in Timber Buildings" works by reducing the number of effective layers. A simplified method to calculate the number of effective layers is presented in the Swedish CLT-handbook.

3.3 Energy and moisture

Measurements and simulations show that buildings made of wood are similar to other building material when it comes to achieving an energy efficient building [15]. Wood is often perceived as a pleasant interior surface since it does not become very cold when it is cold outside. This is due to the low coefficient of thermal conductivity. Wood also has a high thermal storage capacity despite its low density.

3.4 Acoustics and vibrations

Sound and sound isolation should be considered in every building project and not just when wood is involved. As with other parts of designing a building, the result is often the best if taken into account early in the process. Measurements [15] have shown that it is possible to achieve a good acoustic environment in wooden buildings. Sound with low frequency is the hardest to insulate against. These frequencies normally originate from walking, known as step sound.

Vibrations can either be transmitted through the air or the structure itself, the latter being more complicated to reduce [16]. The type of noise that vibrations causes can be perceived as annoying depending on multiple factors including the vibration sensitivity of the building and human perception. These factors needs to be taken in account when designing buildings

The problem with the low frequencies is especially hard for light constructions, which crosslam is. Therefore it is crucial to design the floor structures in a adequate way since it is expensive to modify the structure when it has been finalized.

4. Crosslam properties

The structural properties of crosslam are similar to the structural properties of wood. The strength varies with the angle between the grain and the load. The material strength is reduced when the moisture content is increased. It is also reduced when elements are exposed to a long term load. The material properties vary both within a board and between crosslam elements, more so than in steel and concrete. The structure of crosslam with crosswise placed boards contributes to even out the natural variations of the wood. Crosslam is built up of at least 3 and usually a maximum of 7 layers of boards placed and glued perpendicular to surrounding layers. Some manufacturers have produced crosslam in up to 9 layers. The layers are normally arranged symmetrical but this may vary. The strength of the crosslam elements in each direction is largely determined by the composition of the cross-section. The structure of the material makes the outermost placed layers the most exposed to stresses that occur when the element is bent. The outermost layers are therefore normally oriented longitudinal to the length of the element. However, the transverse layers are exposed to the largest rolling shear load. The main challange in design of wooden floor structures in the serviceability limit state is to achive sufficient stiffness and to limit the risk of annoying vibrations. Design with respect to ultimate limit state and load bearing capacity, is in general not the limiting factor for wooden floor structures [15].

4.1 Design and calculation models

As with all structural designs, the load-effect must not exceed the loadbearing capacity. Crosslam in Sweden is designed with the partial factor method, designed of the ultimate limit state and the serviceability limit state. In the ultimate limit state the structures are checked for failure to minimise the risk of injuries and in the serviceability limit state the structures are designed to ensure accepteble performance of the structure at normal use, e.g. by limiting maximum deformation and vibrations. In Sweden, it is the National Board of Housing that regulates the standards for design [15].

Until 2017, crosslam was designed either with the individual boards in a cross-section, or with instruction from the suppliers. In 2017 a crosslam-manual was released from Swedish Wood, which is a part of the trade organisation Swedish Forest Industry. This because design of crosslam is not part of Eurocode 5. A new version of the Eurocode 5 is estimated to be finished in 2021, where crosslam design will be included. The European Committee for Standardisation, CEN, is responsible for the release of the new Eurocode 5 [15].

Crosslam has three main directions (see Fig 4.2), one stiff (x-axis), one weak (y-axis) and one perpendicular to the plane (z-axis). The stiff direction is generally parallel to the fiber direction of the outermost layers. The weak direction is rotated 90 degrees in the plane [15].

k_{mod} is a modification factor depending on load duration, climate class, material, and is for wood-based materials defined in EC5.

Table 4.1: k_{mod} for crosslam elements [15].

Climate class	Load duration				
	Permanent (P)	Long time (L)	Medium time (M)	Short time (S)	Instantaneous (I)
1	0.6	0.7	0.8	0.9	1.1
2	0.6	0.7	0.8	0.9	1.1
3	–	–	–	–	–

4.1.1 Action perpendicular to the plane

A crosslam element can be modelled as a beam if load transfer is mainly in one direction. This is the case if there is an obvious stiff direction. In that case, the beam can be designed according to beam theory. The elastic modulus of the layers in the weak direction is neglected in these calculation models. The stiffness properties named 0 and 90 are in relation to the x-axis and y-axis to the wooden boards within, and not in relation to the crosslam element.

For crosslam exposed to bending about its y-axis, design with respect to bending stress can according to [15] be carried out according to:

$$\sigma_{m,y,d} = \frac{M_{y,d}}{W_{x,net}} \leqslant f_{m,xlay,d} = k_{sys} \cdot k_{mod} \frac{f_{m,xlay,k}}{\gamma_M} \tag{4.1}$$

M_d Design bending moment
$W_{x,net}$ Net cross-section bending resistance
$f_{m,xlay,d}$ Design flexural strength
$f_{m,xlay,k}$ Charachteristic flexural strength
k_{sys} System factor
k_{mod} Modification factor
γ_M Partial coefficient for crosslam in Sweden γ_M=1,25

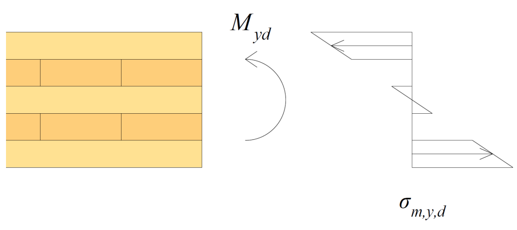


Figure 4.1: Bending stress about the y-axis

For crosslam exposed to bending about its x-axis, design with respect to bending stress can according to [15] be carried out with:

$$\sigma_{m,x,d} = \frac{M_{x,d}}{W_{y,net}} \leqslant f_{m,ylay,d} = k_{sys} \cdot k_{mod} \frac{f_{m,ylay,k}}{\gamma_M} \tag{4.2}$$

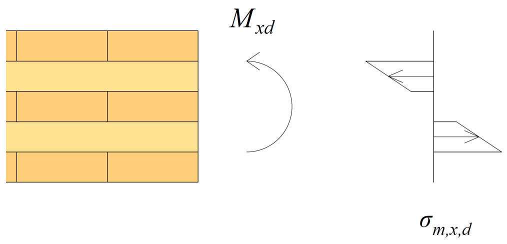


Figure 4.2: Bending stress about the x-axis

For crosslam elements exposed to shear force perpendicular to the plane, shear stress emerges within the element. Verification of shear stress parallel to the fibre direction according to [15] in layer 3, see Fig 4.5:

$$\tau_{v,xz,d} = \frac{S_{x,net} \cdot V_{xz,d}}{I_{x,net} \cdot b_x} \leq f_{v,090,ylay,d} = k_{mod} \frac{f_{v,090,ylay,k}}{\gamma_M} \tag{4.3}$$

$V_{xz,d}$	Design shear force
$S_{x,net}$	Static moment of inertia
$f_{v,090,ylay,d}$	Design longitudinal shear for wooden boards
$f_{v,090,ylay,k}$	Characteristic longitudinal shear for wooden boards

Verification of shear stress in transversal layers according to [15] in layers 2 or 4, see Fig 4.5:

$$\tau_{Rv,yz,d} = \frac{S_{R,y,net} \cdot V_{yz,d}}{I_{y,net} \cdot b_y} \leq f_{v,9090,xlay,d} = k_{mod} \frac{f_{v,9090,xlay,k}}{\gamma_M} \tag{4.4}$$

$V_{xz,d}$	Design shear force
$S_{R,y,net}$	Static moment of inertia
$f_{v,9090,ylay,d}$	Design rolling shear for wooden boards
$f_{v,9090,ylay,k}$	Characteristic rolling shear for wooden boards

4.1.2 In-plane action

Structural design of walls and columns can be made with linear buckling theory according to Eurocode 5. To take the second order theory into account, the reduction factor k_c is used. Generally, there are two load cases in designing walls and columns, transverse load and axial compressive load. If the two load cases are combined, the following equations must be met [15].

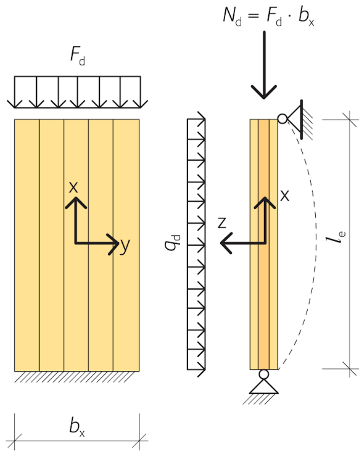


Figure 4.3: Action in the plane.

$$\frac{\sigma_{c,x,d}}{k_{c,y} \cdot f_{c,0,xlay,d}} + \frac{\sigma_{m,y,d}}{f_{m,xlay,d}} \leqslant 1 \tag{4.5}$$

$$\frac{N_d}{k_{c,y} \cdot A_{x,net} \cdot f_{c,0,xlay,d}} + \frac{M_{y,d}}{W_{x,net} \cdot f_{m,xlay,d}} \leqslant 1 \tag{4.6}$$

where the design bending moment $M_{y,d}$ for a uniformly distributed load q_d is given by:

$$M_{y,d} = \frac{q_d \cdot l_e^2}{8} \tag{4.7}$$

and where the reduction factor $k_{c,y}$ is defined by:

$$k_{c,y} = \frac{1}{k_y + \sqrt{k^2 - \lambda_{rel,y}^2}} \leqslant 1 \tag{4.8}$$

where:

$$k_y = 0.5\left(1 + 0.1\left(\lambda_{rel,y} - 0.3\right) + \lambda_{rel,y}^2\right) \tag{4.9}$$

$$\lambda_{rel,y} = \frac{\lambda_y}{\pi}\sqrt{\frac{f_{c,0,xlay,k}}{E_{0,x,05}}} \tag{4.10}$$

is the relative slenderness ratio for bending around the y-axis.

$$\lambda_y = \frac{L}{i_{x,ef}} \tag{4.11}$$

is the slenderness factor (see equation 4.28, 4.29) where $i_{x,ef}$ is the slenderness ratio and L is the buckling length with $L = \beta \cdot l_e$. $E_{0,x,05}$ is the characteristic modulus of elasticity which according to [15] can be determined as:

$$E_{0,x,05} = k \cdot E_{0,x,mean} \tag{4.12}$$

where:

$$k = 1 - \frac{0,328}{\sqrt{\frac{2 \cdot b_x}{0,15} - 1}} \tag{4.13}$$

with b_x in meters and according to Fig 4.3

In cases where $\lambda_{rel} < 0.3$ the risk of buckling is negligible and the following relationship must be verified:

$$\left(\frac{\sigma_{c,x,d}}{f_{c,0,xlay,d}}\right)^2 + \frac{\sigma_{m,y,d}}{f_{m,xlay,d}} \leqslant 1. \tag{4.14}$$

.

4.1.3 The Gamma-method

The Gamma-method can be used to calculate the element bending stiffness in an aproximate manner. By using a simplified calculation method the effective moment of inertia can be calculated for symmetrical 3-, and 5-layered crosslam elements. The Gamma method takes in account the span of the element and reduces the moment of inertia with a reduction factor γ_i [15]. The span used in the calculations is a reference length, l_{ref}, defined as:

- For a simply supported beam $l_{ref} = L$.
- For a continuous beam $l_{ref} = 0.8 \cdot L$, where L is the length of the span in question.
- For a cantilever beam $l_{ref} = 2 \cdot L$, where L is the length of the beam.

For **3-layered** crosslam elements, every layer is numbered from the bottom up from 1 to n. The rolling shear modulus G_R and the modulus of elasticity E_x is also taken in account.

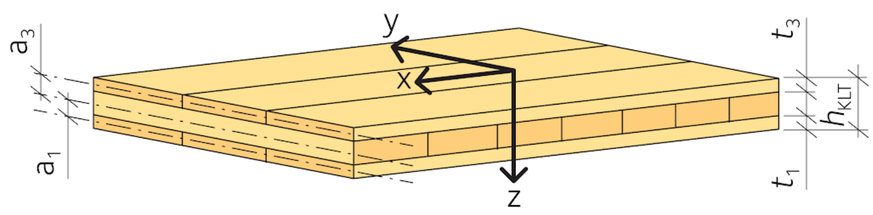


Figure 4.4: Directions and geometry parameters for 3-layered crosslam elements.

$$\gamma_1 = 1 \tag{4.15}$$

$$\gamma_3 = \frac{1}{1 + \frac{\pi^2 E_{x,3} t_3}{l_{ref}^2} \cdot \frac{t_2}{G_{9090,2}}} \tag{4.16}$$

The distances a_1 and a_3 can be calculated with:

$$a_1 = \frac{\gamma_3 \frac{E_{x,3}}{E_{ref}} b t_3 \left(\frac{t_1}{2} + t_2 + \frac{t_3}{2}\right)}{\gamma_1 \frac{E_{x,1}}{E_{ref}} b t_1 + \gamma_3 \frac{E_{x,3}}{E_{ref}} b t_3}. \tag{4.17}$$

For symmetrical lay-ups with the same stiffness, $E_{i,x}$ the following applies:

$$a_3 = \frac{t_1}{2} + t_2 + \frac{t_3}{2} - a_1. \tag{4.18}$$

The effective moment of inertia:

$$I_{x,ef} = \sum \frac{E_{x,i}}{E_{ref}} \cdot \frac{b_x t_i^3}{12} + \gamma_i \frac{E_{x,i}}{E_{ref}} b_x t_i a_i^2. \tag{4.19}$$

For symmetrical cross-sections $(t_1 = t_3)$ with the same strength grade the following applies:

$$I_{x,ef} = \frac{b_x t_1^3}{12} + b_x t_1 a_1^2 + \frac{b_x t_3^3}{12} + \gamma_3 b_x t_3 a_3^2. \tag{4.20}$$

For **5-layered** crosslam elements the same applies as for 3-layered, with the exception of another added layer:

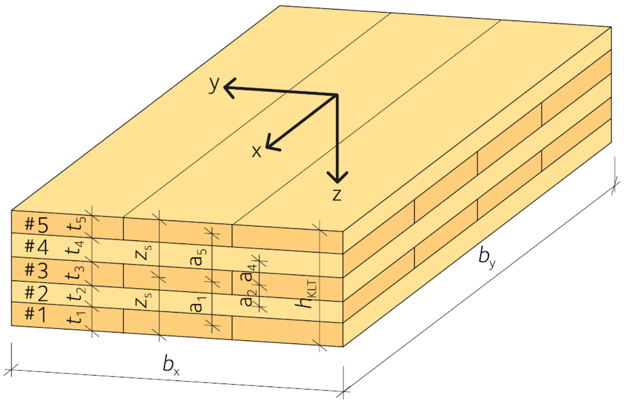


Figure 4.5: Directions and geometry parameters for 5-layered crosslam elements.

$$\gamma_1 = \frac{1}{1 + \frac{\pi^2 E_{x,1} t_1}{l_{ref}^2} \cdot \frac{t_2}{G_{9090,2}}} \tag{4.21}$$

$$\gamma_3 = 1 \tag{4.22}$$

$$\gamma_5 = \frac{1}{1 + \frac{\pi^2 E_{x,5} t_5}{l_{ref}^2} \cdot \frac{t_4}{G_{9090,4}}}. \tag{4.23}$$

For symmetrical cross-sections $(t_1 = t_3 = t_5)$ and same strength class the following applies. The distances a_1, a_3 and a_5 can be calculated with:

$$a_3 = \frac{\gamma_1 \frac{E_{x,1}}{E_{ref}} b t_1 \left(\frac{t_1}{2} + t_2 + \frac{t_3}{2}\right) - \gamma_5 \frac{E_{x,5}}{E_{ref}} b t_5 \left(\frac{t_3}{2} + t_4 + \frac{t_5}{2}\right)}{\gamma_1 \frac{E_{x,1}}{E_{ref}} b t_1 + \gamma_3 \frac{E_{x,3}}{E_{ref}} b t_3 + \gamma_5 \frac{E_{x,5}}{E_{ref}} b t_5}. \tag{4.24}$$

For symmetrical cross-sections $(t_1 = t_3 = t_5)$ and same strength class the following applies:

$$a_1 = \frac{t_1}{2} + t_2 + \frac{t_3}{2} - a_3 \tag{4.25}$$

$$a_3 = 0 \tag{4.26}$$

$$a_5 = \frac{t_3}{2} + t_4 + \frac{t_5}{2} - a_3. \tag{4.27}$$

The effective moment of inertia follows:

$$I_{x,ef} = \sum \frac{E_{x,i}}{E_{ref}} \cdot \frac{b_x t_i^3}{12} + \gamma_i \frac{E_{x,i}}{E_{ref}} b_x t_i a_i^2. \tag{4.28}$$

For symmetrical cross-sections $(t_1 = t_3 = t_5)$ and same strength class the following applies:

$$I_{x,ef} = b_x \left(\frac{3 \cdot t_1^3}{12} + 2\gamma_1 t_1 a_1^2 \right). \tag{4.29}$$

If there is risk of buckling, the shear deformations within the transverse layers must be taken into account. This is done by calculating the buckling length l_e as the reference length l_{ref}. $A_{x,net}$ and $A_{y,net}$ are the net cross-section areas.

$$i_{x,ef} = \sqrt{\frac{I_{x,ef}}{A_{x,net}}} \tag{4.30}$$

$$i_{y,ef} = \sqrt{\frac{I_{y,ef}}{A_{y,net}}}. \tag{4.31}$$

4.2 Parametric study using the Gamma-method

Since stiffness, primarily in floor structures, is a limiting factor when using wood as a construction material [15], a parametric study has been done to examine potential benefits of using wood species with a higher rolling shear modulus. The rolling shear modulus of a wood species is important for crosslam elements stiffness since the transverse layers transfer the force between the longitudinal layers. The study has been conducted using the Gamma-method. In the study, the rolling shear modulus varied between 20 and 200 MPa while all other variables were held constant. The modulus of elasticity was set at 11,000 MPa and two spans, 4 and 8 meters, were examined. The results are presented in Fig 4.7 (3-layer) and 4.8 (5-layer). As presented in the diagrams, the influence of the rolling shear modulus is proportionately larger for short spans than for longer spans. The study also shows that the rolling shear modulus has a larger influence if there are more layers in the element. The wood species tested in the dissertation have a higher rolling shear modulus than spruce, as presented in Table 3.1.

Since a 3-layered element with an 8 meter span and a 5-layered element with a 4 meter span might not be realistic, another graph is presented showing the relation between deflection and rolling shear modulus, see Fig 4.6. The load, q, has been set to 4 kN/m^2 on a 3-layered element with a span of 4 meter and a 5-layered element with a span of 8 meter to represent a realistic case. Each layer is 0,04 meter thick.

The different strengths and moduli vary depending on the origin. Some reports claims a rolling shear modulus of spruce, 100 MPa [17], double that of the modulus stated in "KL-Trähandboken" that is used in the dissertation. The rolling shear modulus is dependent on geometry and orientations of the annual rings of the cross-section.

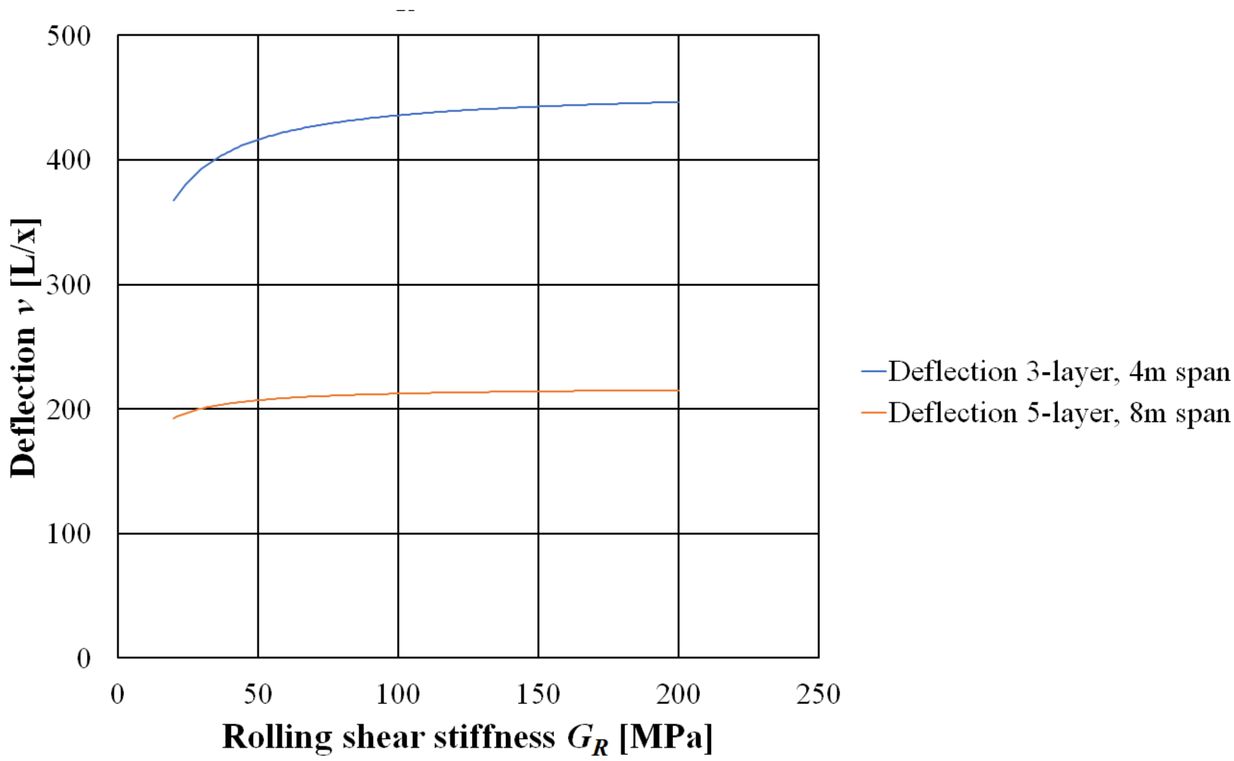


Figure 4.6: Influence of G_R on an elements deflection ($q = 4kN/m^2$).

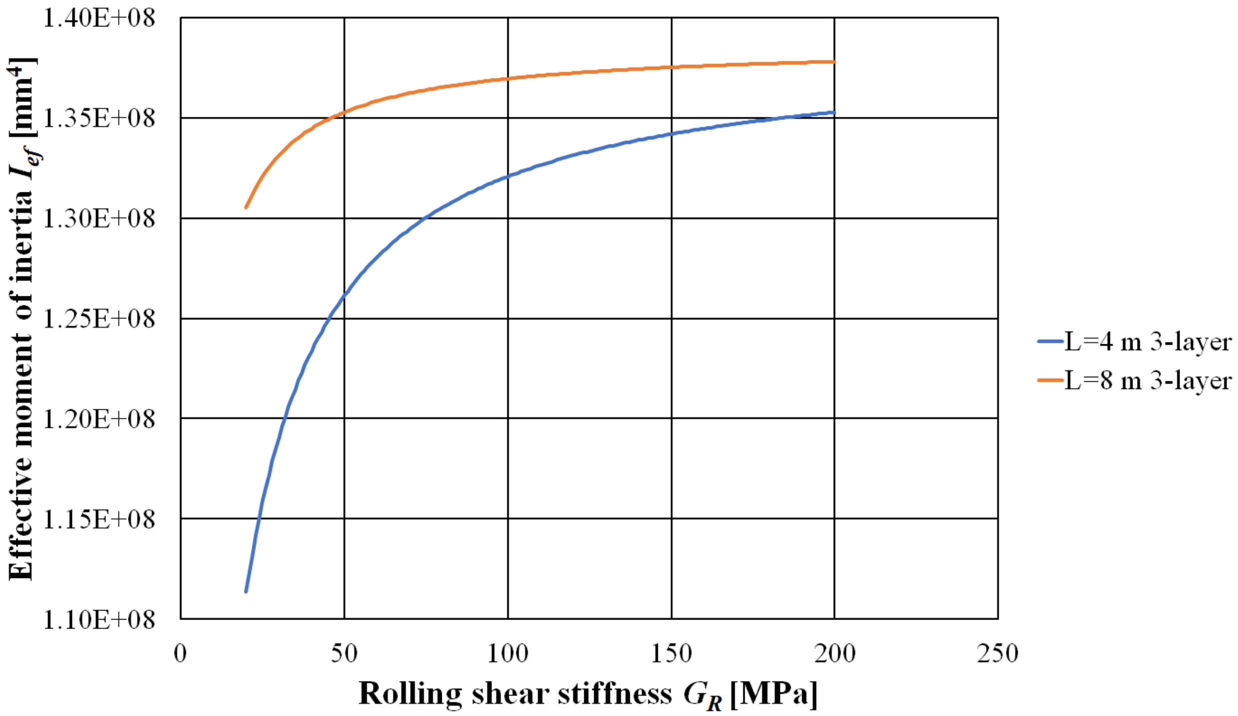


Figure 4.7: 3 layer element, 40-40-40 [mm].

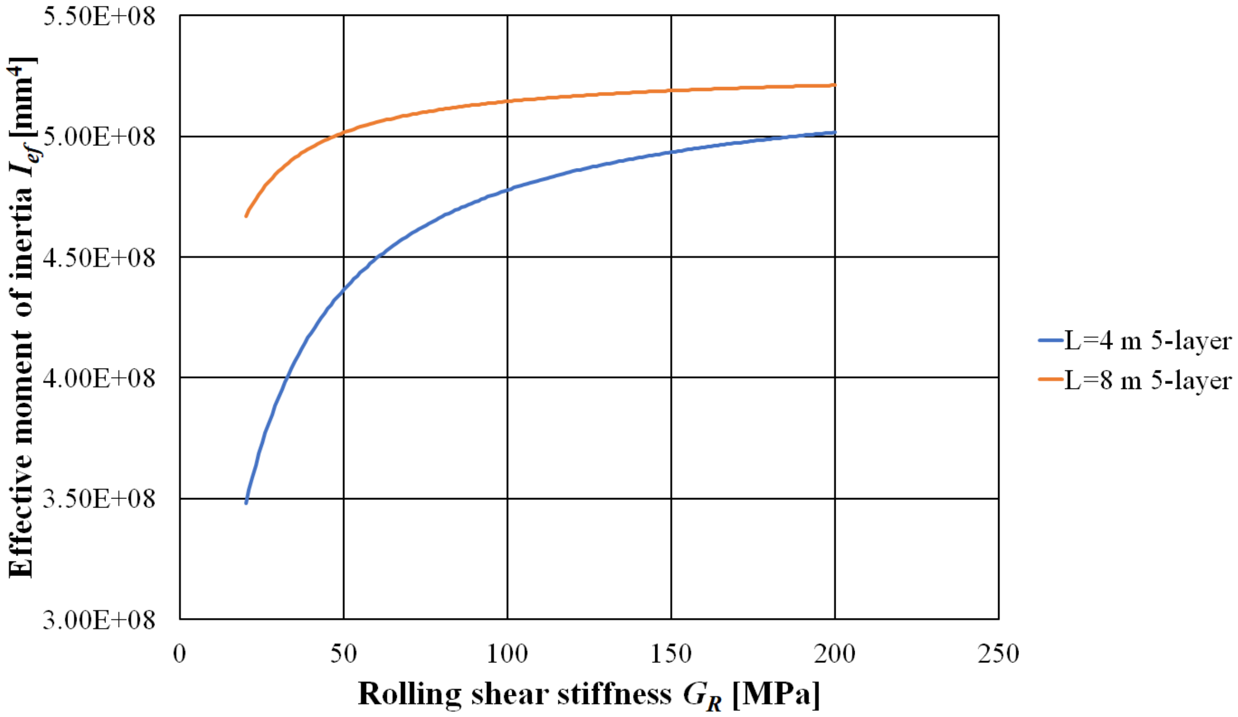


Figure 4.8: 5 layer element, 40-40-40-40-40 [mm].

5. Shear tests with new wood species for crosslam

The purpose of the experimental part of the dissertation is to examine if the use of other wood species than Spruce is beneficial in terms of the strength and stiffness of a crosslam element. 45 test specimens of five different types have been tested. The tests have been carried out with an MTS 810, a servo-hydraulic testing machine, at Lund University in April 2018. The maximum load of each specimen is taken from the deformation/load diagram registered from the test.

5.1 Manufacturing of the test specimens

The specimens have been manufactured in five different combinations.

Combination I	Birch - Spruce - Birch
Combination II	Birch - Hybrid Aspen - Birch
Combination III	Birch - Poplar - Birch
Combination IV	Hybrid Aspen - Poplar - Hybrid Aspen
Combination V	Spruce - Spruce - Spruce (Reference.)

The Poplar, Birch and Hybrid Aspen comes from a cultivation on former farmland on Sätuna Säteri, Sweden. The trees were planted in the spring of 1991 and cut down in february 2018. The spruce is from the area around Uppsala, Sweden, although the exact location is unknown.

Before manufacturing each test specimen, all wood has been weighed. With that information, a density has been calculated (see Table 5.1).

The specimens were glued with a MUF-adhesive, resin p4546 and hardener p5022. When glued, resin and hardener were mixed before application. The proportion between resin and hardener was 100:30. The joints were glued in two ways. On one side of the middle section 200 g/m^2 glue was applied on both faces. On the other side one face had 400 g/m^2 glue applied. The total amount of glue was the same in all joints.

Table 5.1: Average density of wood used for specimens.

Wood type	**Mean density [kg/m^3]**
Birch	590
Hybrid aspen	454
Poplar	428
Spruce	495

Figure 5.1: Specimen before the test.

(a) Poplar (b) Hybrid aspen

Figure 5.2: Photographs of the the trees being cut down at Sätuna Säteri. Copyright Agne Helmö.

5.2 Experimental work

The test setup is shown in Fig 5.3. The specimen was placed in the centre of the hydraulic press. To avoid eccentric load, two steel plates and a centrically placed steel ball were used. To avoid that the supporting parts of the specimens moved outwards, stops were placed. The goal was to achieve the maximum load within 3–5 minutes. Therefore, the rate of loading varied between 0.008–0.033 mm/s depending on the type of specimen. Unfortunately the desired time was not always achieved due to the differing quality and stiffness of the specimens.

The specimens were placed in a climate room before the tests with the constant temperature 20°C and 60% relative humidity. The specimens were left to acclimatize for a couple of weeks while one specimen from every combination was weighed at four different occasions (Table B.2).

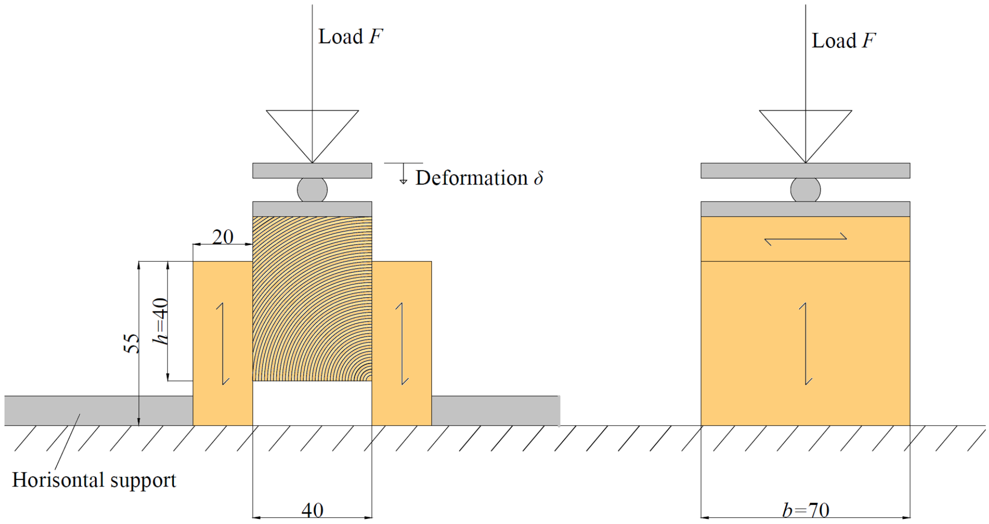


Figure 5.3: Setup in the MTS-Machine (front and side view).

Figure 5.4: Setup in the MTS-Machine.

5.3 Results

A total of 45 specimens, nine of each combination, were tested to obtain reliable data. For every specimen a number of values are presented; maximum load, maximum shear stress, maximum deformation, wood failure percentage (WFP), orientation of annual rings and a category called material failure.

The maximum load, F_{max}, is the highest load recorded by the MTS-machine. The maximum shear stress, τ_{max}, is the maximum load divided by the nominal area $A = 2hb$ (see Fig 5.3) of the two glue joints (5612 mm^2).

The maximum shear stress has been calculated with: $\tau_{max} = \dfrac{F_{max}}{A}$.

F_{max}	maximum load at failure
A	5612 mm^2
τ_{max}	shear stress

The maximum deformation is the deformation recorded by the MTS-machine at the moment of maximum load. The wood failure percentage ($WFP = \frac{A_1}{A_1+A_2}$, see Fig 5.5) is a measure of how much wooden fibres are left on the joint after specimen failure. This assessment has been done by visual inspection of the specimens after splitting them into two parts. The WFP is judged in steps of 25%. This means that a specimen can be sorted into 0%, 25%, 50%, 75%, and 100%. Note that this number is a rough estimate. The second to last category that has been judged is the orientation of the annual rings relative to the load-plate. There are 3 steps, 90, 45 and 0 degrees. The definition of the orientation is presented in Fig 5.6. The last category that has been assessed is "material failure". The definition of a material failure is if a test specimen has reached its maximum load without one of the glue joints breaking. This means that the middle part of the specimen has ruptured or in some way failed. For these cases, WFP is set to 100%. Figures 5.7–5.11 and tables 5.2–5.6 show the results of the tests.

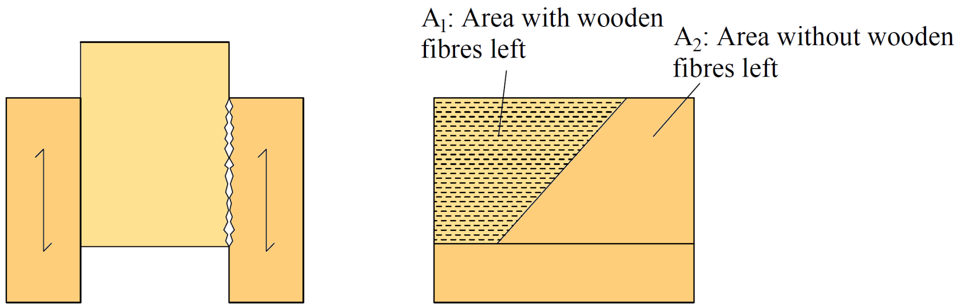


Figure 5.5: Definition of WFP

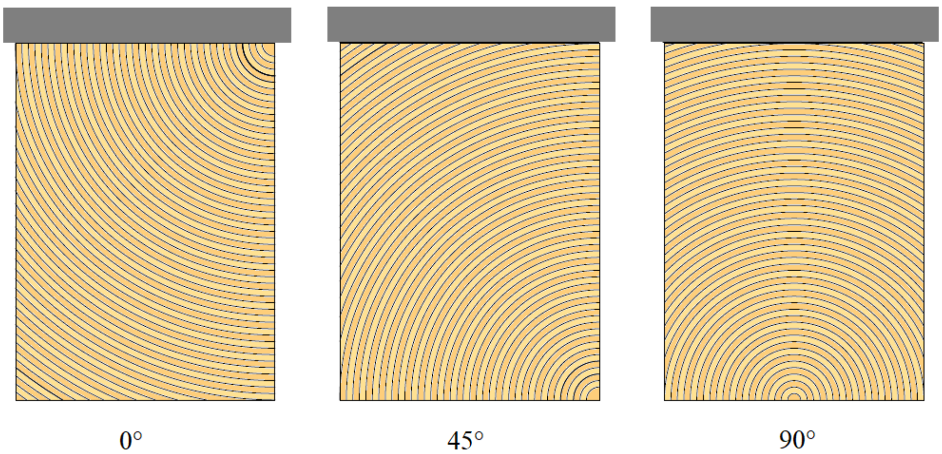


Figure 5.6: Angles of annual rings relative the load plate

Figure 5.7: Combination I Birch-Spruce-Birch

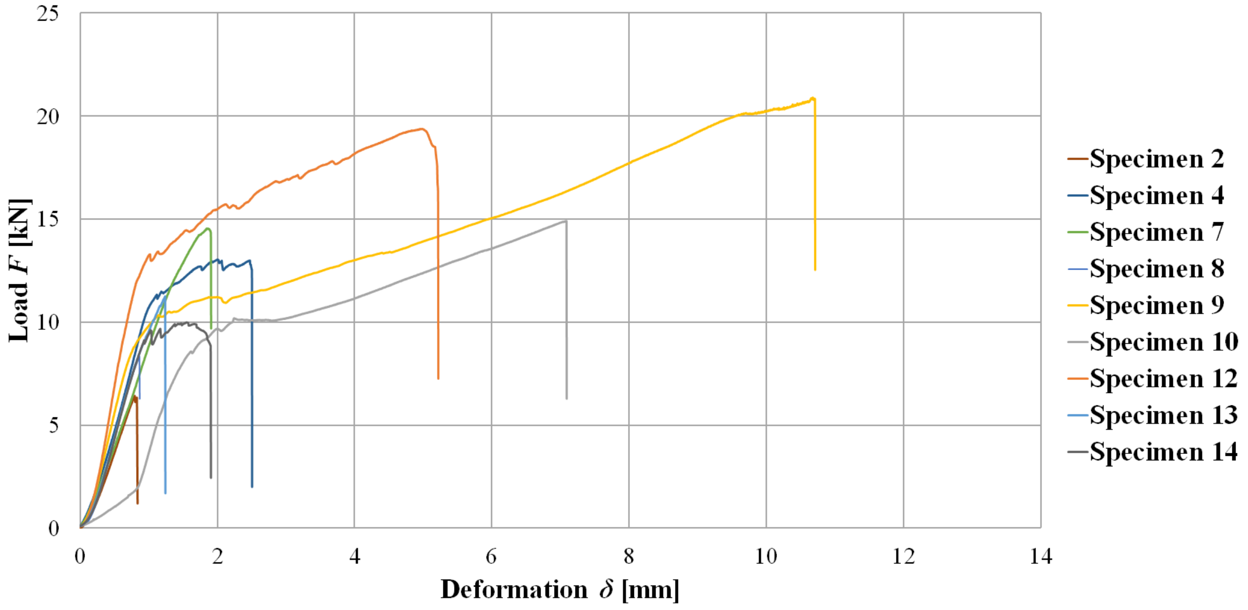


Table 5.2: Combination I Birch-Spruce-Birch

Specimen	**Maximum load F_{max} [kN]**	**Maximum shear stress τ_{max} [MPa]**	**Max deformation δ_{max} [mm]**	**WFP**	**Orientation**	**Material failure**
I_2	6.42	1.15	0.83	25%	45	
I_4	13.0	2.33	2.50	25%	90	
I_7	14.5	2.60	1.90	50%	0	
I_8	8.34	1.49	0.86	0%	0	
I_9	20.9	3.73	10.7	25%	45	
I_10	14.9	2.66	7.09	100%	45	x
I_12	19.4	3.46	5.21	50%	90	
I_13	11.2	2.01	1.24	0%	0	
I_14	9.99	1.78	1.90	25%	0	
Mean	13.2	2.36	3.58			
Standard deviation	4.82	0.86	3.41			

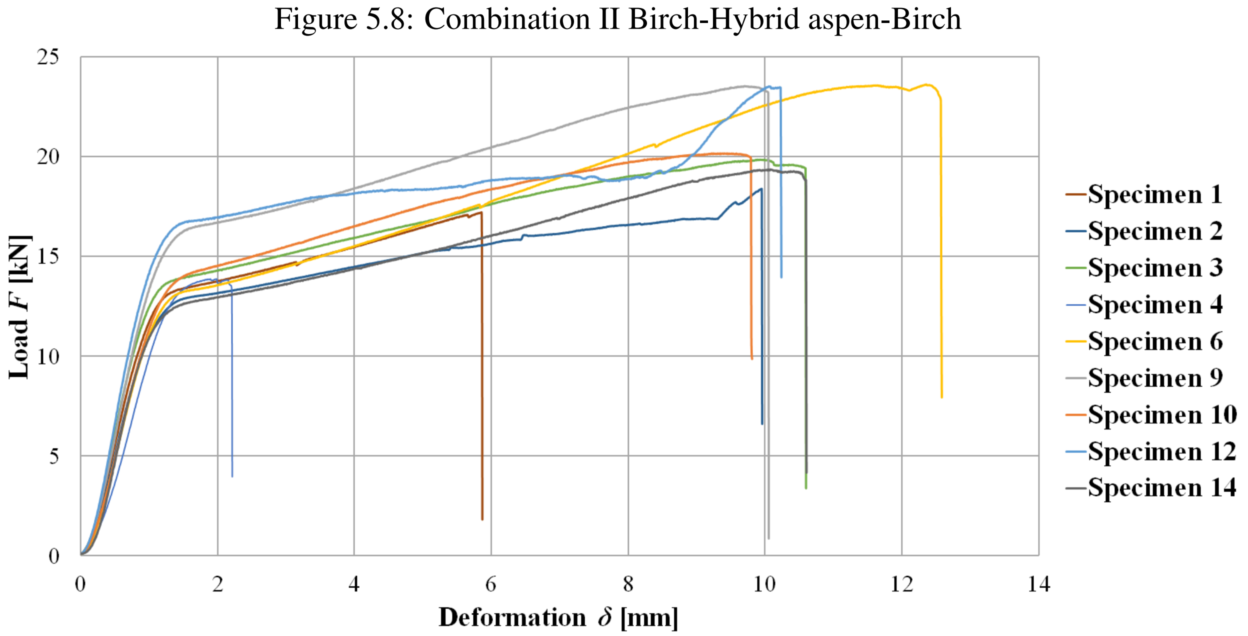


Table 5.3: Combination II Birch-Hybrid aspen-Birch

Specimen	Maximum load F_{max} [kN]	Maximum shear stress τ_{max} [MPa]	Max deformation δ_{max} [mm]	WFP	Orientation	Material failure
II_1	17.2	3.07	5.86	25%	45	
II_2	18.4	3.28	9.95	50%	45	
II_3	19.8	3.54	10.6	50%	45	
II_4	13.9	2.48	2.21	0%	45	
II_6	23.6	4.22	12.6	75%	45	
II_9	23.5	4.20	10.1	100%	45	
II_10	20.2	3.60	9.80	100%	45	x
II_12	23.5	4.20	10.2	100%	45	x
II_14	19.3	3.46	10.6	75%	45	
Mean	19.9	3.56	9.10			
Standard deviation	3.29	0.59	3.12			

Figure 5.9: Combination III Birch-Poplar-Birch

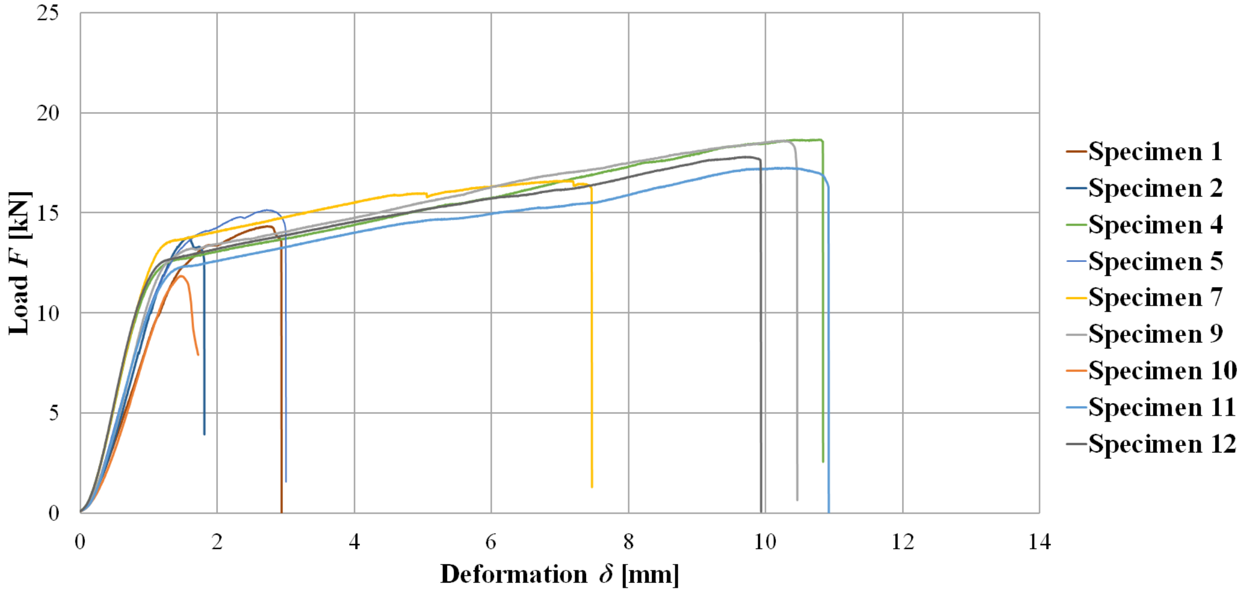


Table 5.4: Combination III Birch-Poplar-Birch

Specimen	**Maximum load F_{max} [kN]**	**Maximum shear stress τ_{max} [MPa]**	**Max deformation δ_{max} [mm]**	**WFP**	**Orientation**	**Material failure**
III_1	14.3	2.56	2.93	75%	90	
III_2	13.9	2.46	1.81	50%	45	
III_4	18.9	3.33	10.8	100%	45	
III_5	15.2	2.71	3.00	75%	90	
III_7	16.6	2.97	7.46	75%	45	
III_9	18.6	3.32	10.5	75%	45	
III_10	11.8	2.11	1.72	50%	90	
III_11	17.3	3.08	10.9	100%	45	x
III_12	17.2	3.07	9.93	50%	45	
Mean	15.9	2.85	6.56			
Standard deviation	2.32	0.41	4.13			

Figure 5.10: Combination IV Hybrid aspen-Poplar-Hybrid aspen

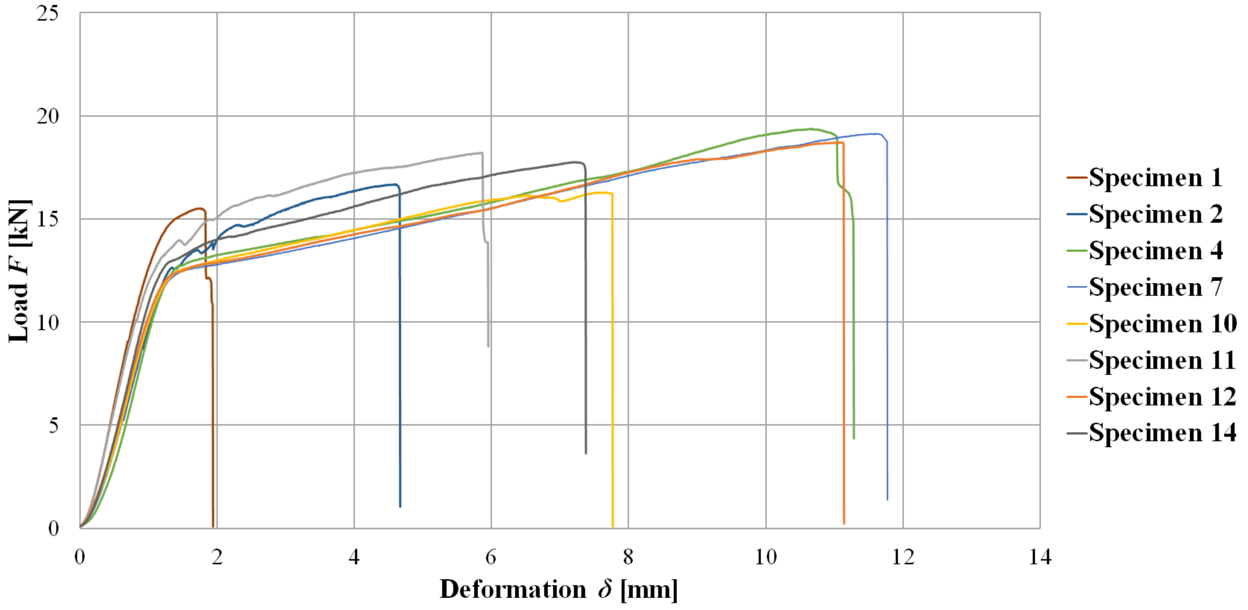


Table 5.5: Combination IV Hybrid aspen-Poplar-Hybrid aspen

Specimen	**Maximum load F_{max} [kN]**	**Maximum shear stress τ_{max} [MPa]**	**Max deformation δ_{max} [mm]**	**WFP**	**Orientation**	**Material failure**
IV_1	15.5	2.77	1.93	75%	90	x
IV_2	16.7	2.98	4.66	25%	90	
IV_4	19.4	3.46	11.1	100%	45	x
IV_7	19.1	3.42	11.8	100%	45	
IV_10	16.3	2.91	7.76	100%	45	x
IV_11	18.2	3.25	5.95	100%	90	x
IV_12	18.7	3.34	11.1	50%	45	
IV_14	17.8	3.17	7.37	75%	45	
Mean	17.7	3.16	7.73			
Standard deviation	1.42	0.25	3.52			

Figure 5.11: Combination V Spruce-Spruce-Spruce

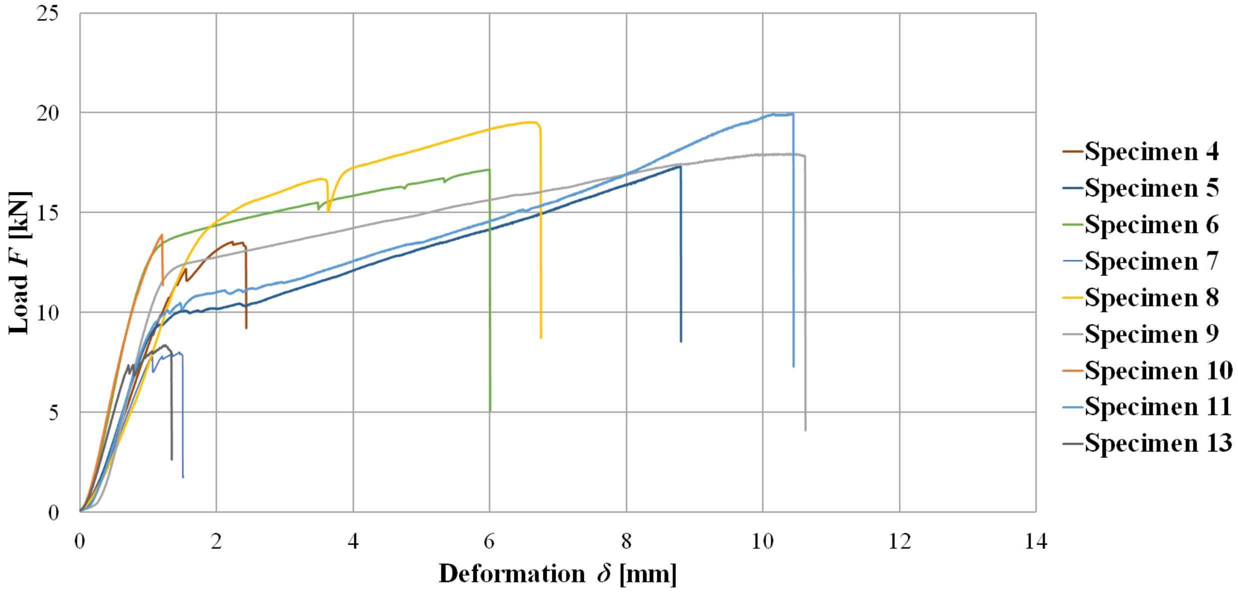


Table 5.6: Combination V Spruce-Spruce-Spruce

Specimen	**Maximum load F_{max} [kN]**	**Maximum shear stress τ_{max} [MPa]**	**Max deformation δ_{max} [mm]**	**WFP**	**Orientation**	**Material failure**
V_4	13.5	2.42	2.43	100%	0	
V_5	17.3	3.09	8.80	100%	45	x
V_6	17.2	3.07	6.00	25%	45	x
V_7	8.03	1.43	1.51	50%	0	
V_8	19.5	3.49	6.75	50%	90	
V_9	18.0	3.21	10.6	100%	0	x
V_10	13.9	2.48	1.21	100%	0	x
V_11	20.0	3.57	10.5	100%	45	x
V_13	8.38	1.50	1.34	100%	0	
Mean	15.1	2.69	5.46			
Standard deviation	4.47	0.80	3.94			

6. Discussion

This chapter discusses observations made during and after the tests and discusses also the results of the parametric study.

6.1 Tests

It should be mentioned that the authors were not involved in the manufacturing of the specimens. Even though the specimens were mostly manufactured adequately, a few glue joints were of poor quality. The glued area of the specimens were meticulously done with a mean area of 5612 mm^2, with only a 33 mm^2 deviation (see Table B.1). The combinations were predetermined before the tests. We do not believe that the combinations tested are the most relevant in terms of a new combination for a production market. We believe that the most relevant combinations to test would be Spruce–New species–Spruce. This because the rolling shear modulus often is a limiting factor in the transverse layers.

When reviewing the data for the different combinations some results are clear. In some of the tests, the glue appeared to be the limiting factor, especially in Combination I (Birch–Spruce–Birch), having the greatest variability of results in terms of maximum load. Furthermore the mean deformation and the mean maximum load is the smallest in combination I. Specimens 2, 7, 8, 13, and 14 have the least deformation of the other specimens in Combination I, 0.86–1.9 mm, together with a low WFP and all but Specimen 2 have the same orientation of annual rings. However Specimen 2, breaking on both glue joints, is probably faulty having the lowest maximum load and least deformation of all 45 specimens, most likely making the glue joints the limiting factor.

Viewing the results from the tests regarding maximum load, it is evident that some combinations were more consistent than others. Combination IV (Hybrid Aspen–Poplar–Hybrid Aspen) had the smallest standard deviation in relation to its mean maximum load. The highest mean maximum load was recorded on Combination II (Birch–Hybrid Aspen–Birch). The lowest maximum load measured was found in Combination I. Combination III (Birch–Poplar–Birch) and V (Spruce–Spruce–Spruce) had similar mean maximum load. However, the standard deviation of Combination V was almost double that of Combination III, showing higher consistency in Combination III.

Regarding the WFP, the glue joints that have the lowest percentage of wooden fibres left, ranks; I, II, III, IV, and V. Combination I, Birch with Spruce, leaving on average 33% fibres left on the glue joints, and Combination V, Spruce, averaging 81% fibre left. This shows that Spruce together with Birch had the poorest adhesion, while Spruce together with Spruce had the best adhesion.

The combination with highest standard deviation relative to mean deformation was Combination I with a mean deformation of 3.58 mm and standard deviation of 3.41 mm. The most consistent combination was Combination II, with a mean deformation of 9.10 mm and standard deviation of 3.12 mm.

In Combinations IV and V, there is a higher share of material failure in the specimens, meaning that the cross layer has cracked before or simultaneously as the glue joints. This could be due to high tension stress (perpendicular to the grain) at the bottom of the middle part of the specimen. It could also depend on the rolling shear strength. This is interesting since Combination V is the reference combination, meaning that the specimen could potentially be improved by changing the cross layer to an other wood species.

6.2 Parametric study

In the parametric study, elements of crosslam constructed with one wood species are compared. The parametric study shows an increased moment of inertia with a higher rolling shear modulus in both 3-, and 5-layer elements. However, this growth decreases when increasing the roll shear modulus. To compare the extremes, one can compare Spruce (G_R=50 MPa) with Birch (G_R=175 MPa). The gain in moment of inertia is relatively small, with a maximum of 14% on a 4 m long 5-layered crosslam element. On a 8 m long, 3-layered crosslam element, there is a 2% gain when switching to Birch.

7. Concluding remarks

7.1 Conclusions

The findings in the dissertation suggest that the main reason for the small number of projects in crosslam today is a lack of experience of usage in the industry. Mainly contractors do not want to take the risk to work with crosslam when they are more experienced with steel and concrete. Another problem is that many buildings are designed to be built in steel or concrete. If a building designed for steel or concrete is redesigned to be built in wood it normally becomes more expensive. The buildings need to be designed in wood from the start.

The findings also show that implementation of new wood species in crosslam elements can be beneficial for the elements strength and stiffness. In the test, all specimens with another wood type than spruce performed well in regard to material strength, the limiting factor was often the glue joints. This might indicate that if more work is done to improve these, new wood species can improve crosslam elements properties. Considering the parametric study, it might not be beneficial enough to change wood species to strengthen crosslam elements until further research is made. However, since the reference combination (Combination V) has the highest rates of material failure, it might indicate that the higher rolling shear strengths in the other tested combinations could provide stronger crosslam elements if needed.

7.2 Further research

We think that if further tests are to be done, only the wood species in the cross layers (Spruce–New species–Spruce), should be changed due to the potential benefits in strength with a higher rolling shear modulus. We also believe that the orientation of the annual rings should be the same in all test specimens. In our tests both orientation, the outer layer species, and the middle layer species varied which made it difficult to evaluate the results.

Based on the first part of this report, we also believe there is more research to be done about people's thoughts about crosslam. This knowledge could be used to facilitate work with wood and crosslam.

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Appendices

A. Results of tested specimens

Figure A.1: Specimen I-2

Figure A.2: Specimen I-4

Figure A.3: Specimen I-7

Figure A.4: Specimen I-8

Figure A.5: Specimen I-9

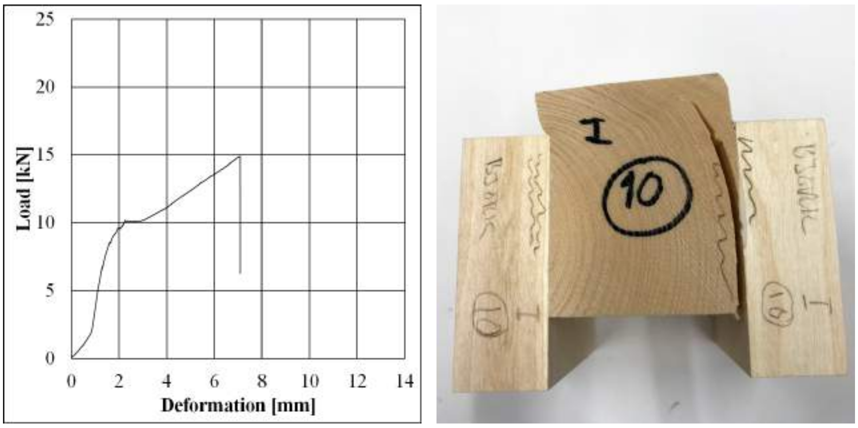

Figure A.6: Specimen I-10

Figure A.7: Specimen I-12

Figure A.8: Specimen I-13

Figure A.9: Specimen I-14

Figure A.10: Specimen II-1

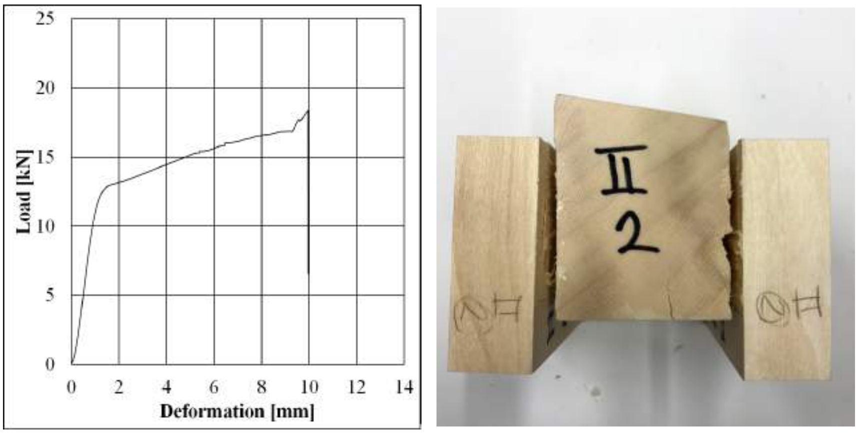

Figure A.11: Specimen II-2

Figure A.12: Specimen II-3

Figure A.13: Specimen II-4

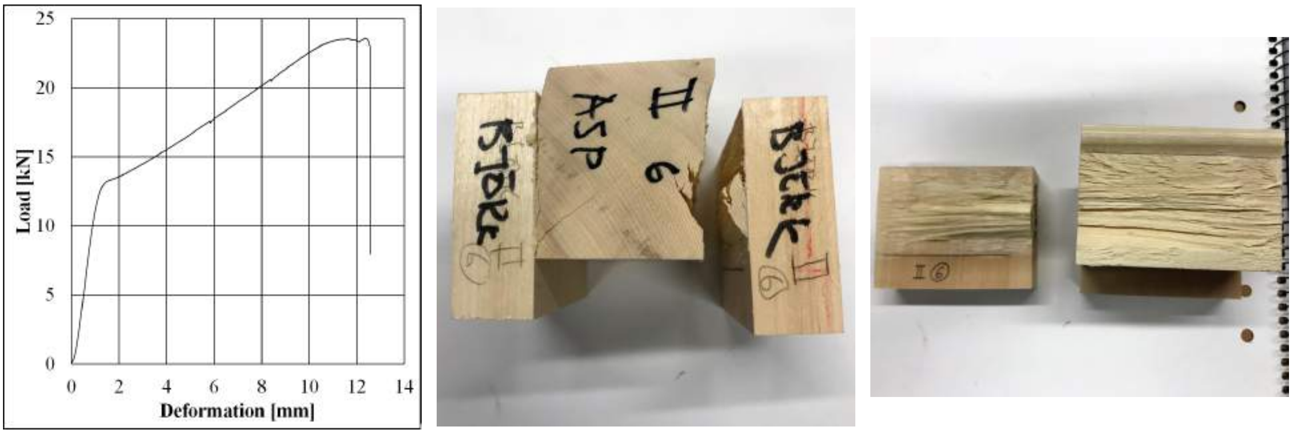

Figure A.14: Specimen II-6

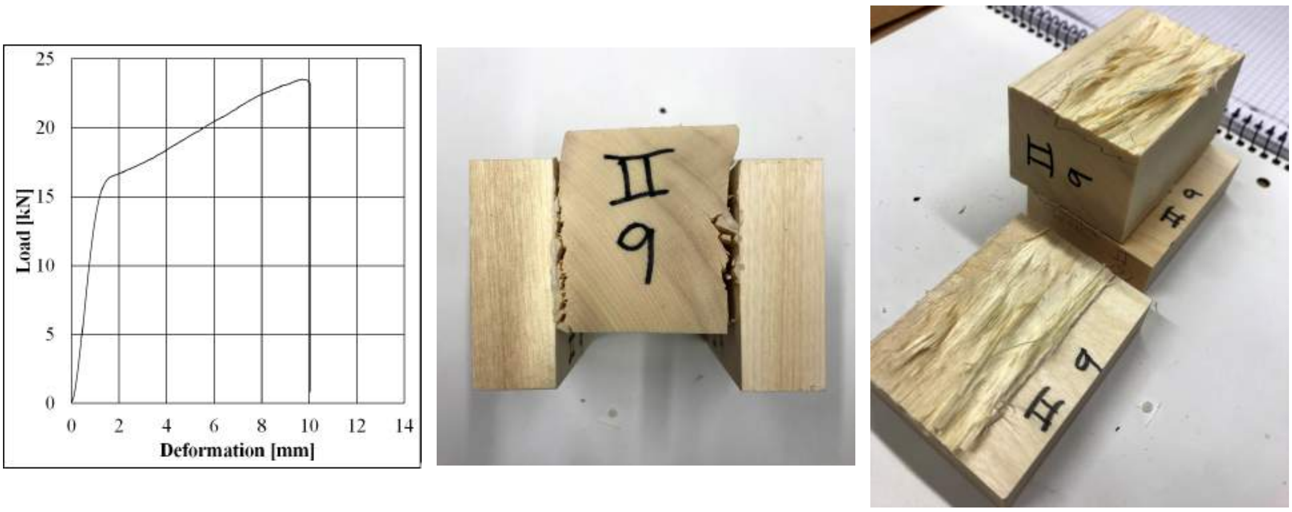

Figure A.15: Specimen II-9

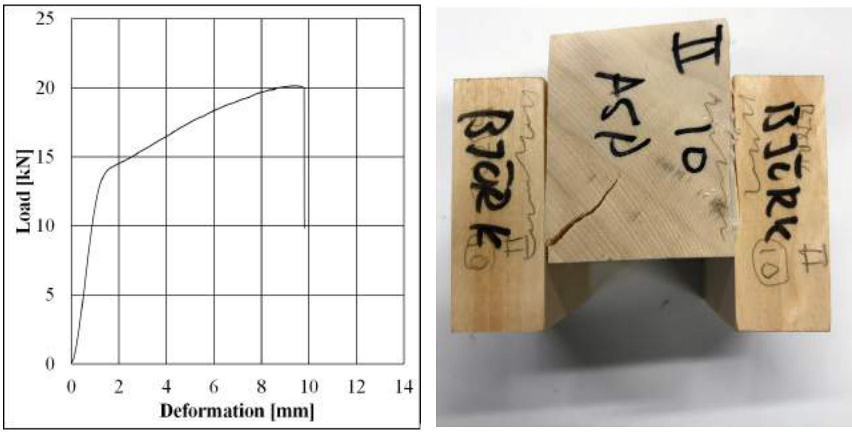

Figure A.16: Specimen II-10

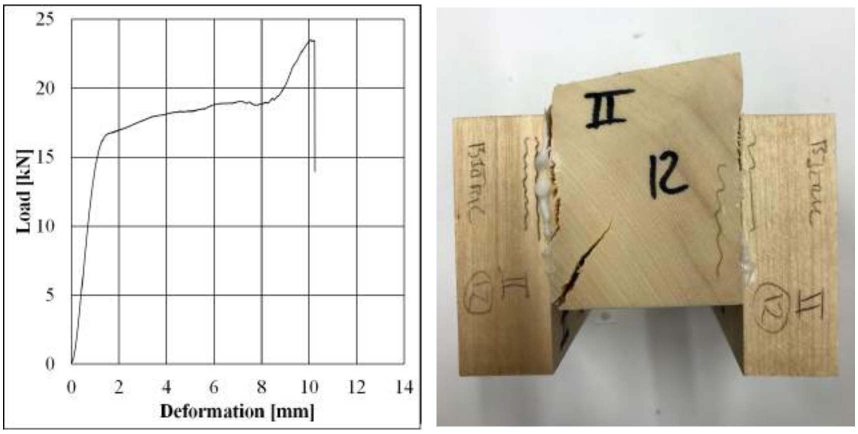

Figure A.17: Specimen II-12

Figure A.18: Specimen II-14

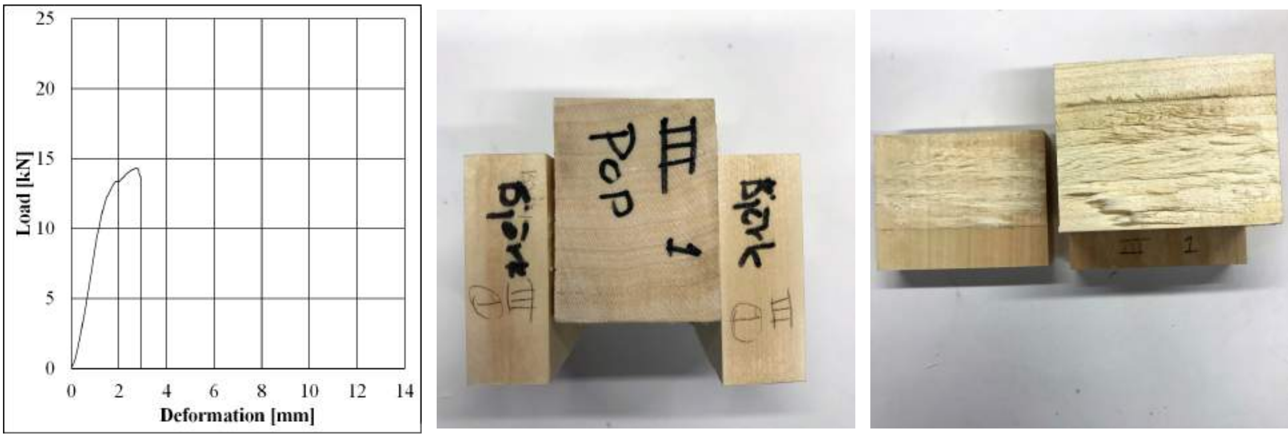

Figure A.19: Specimen III-1

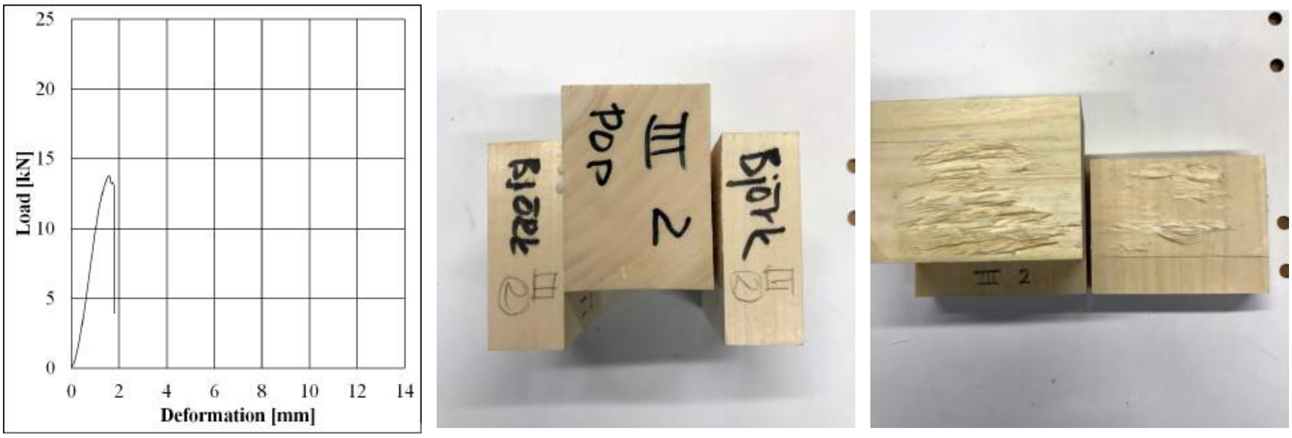

Figure A.20: Specimen III-2

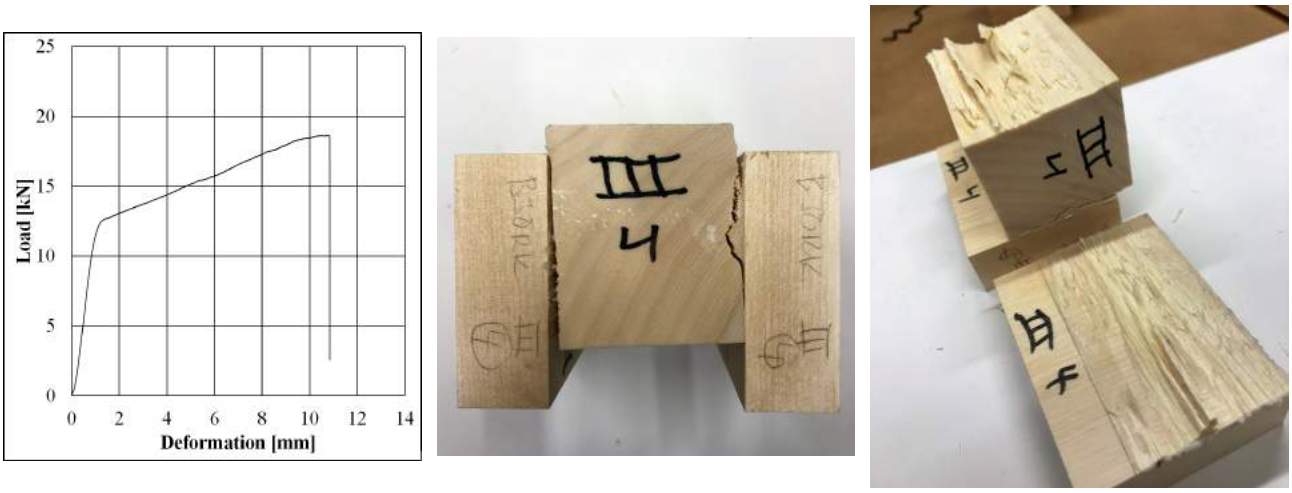

Figure A.21: Specimen III-4

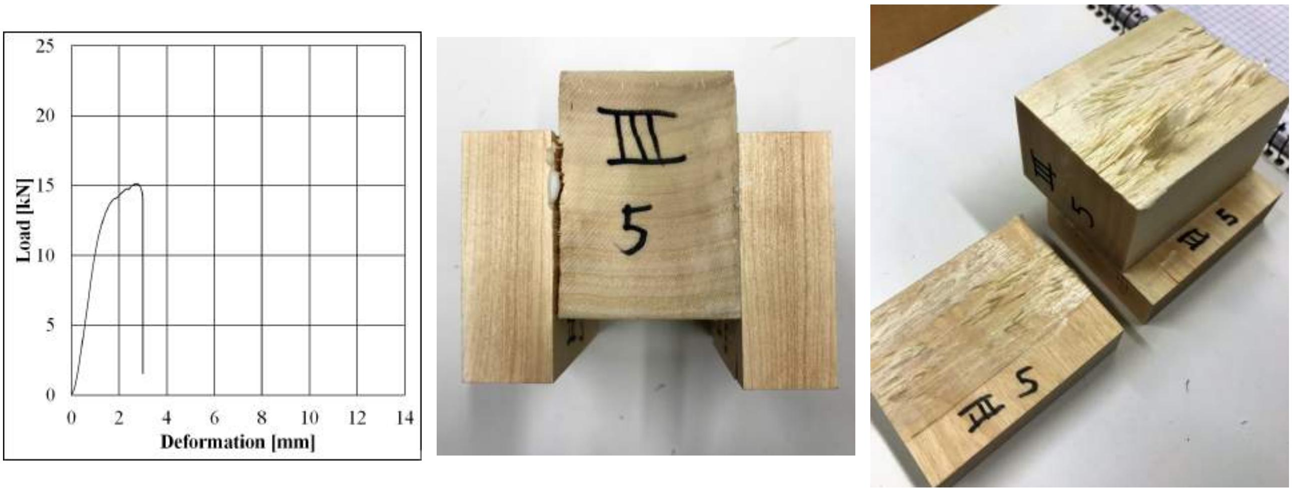

Figure A.22: Specimen III-5

Figure A.23: Specimen III-7

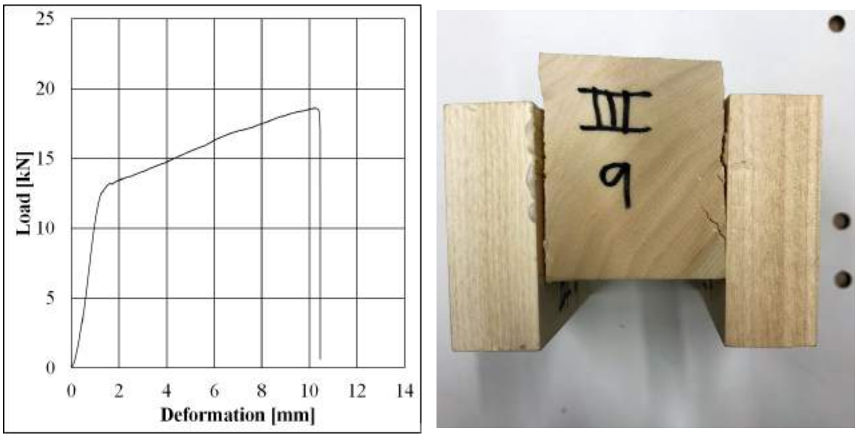

Figure A.24: Specimen III-9

Figure A.25: Specimen III-10

Figure A.26: Specimen III-11

Figure A.27: Specimen III-12

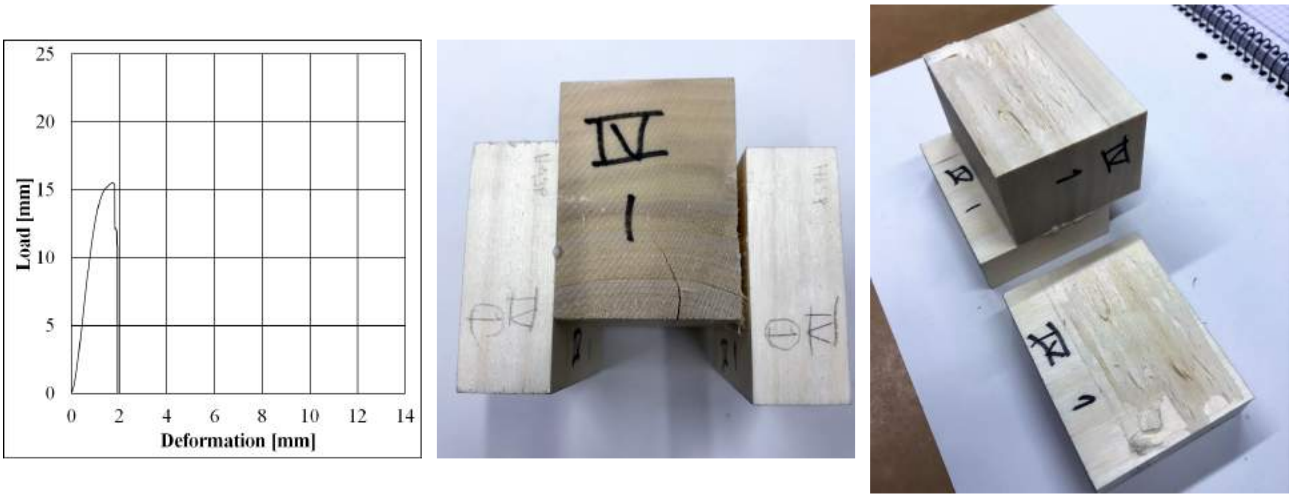

Figure A.28: Specimen IV-1

Figure A.29: Specimen IV-2

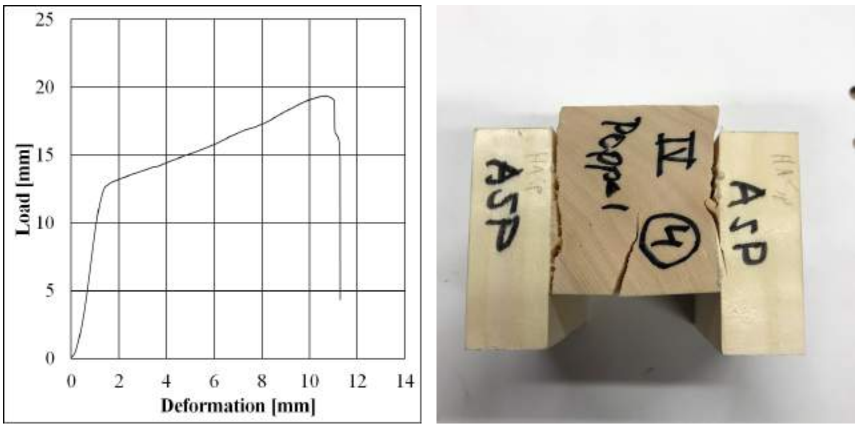

Figure A.30: Specimen IV-4

Figure A.31: Specimen IV-7

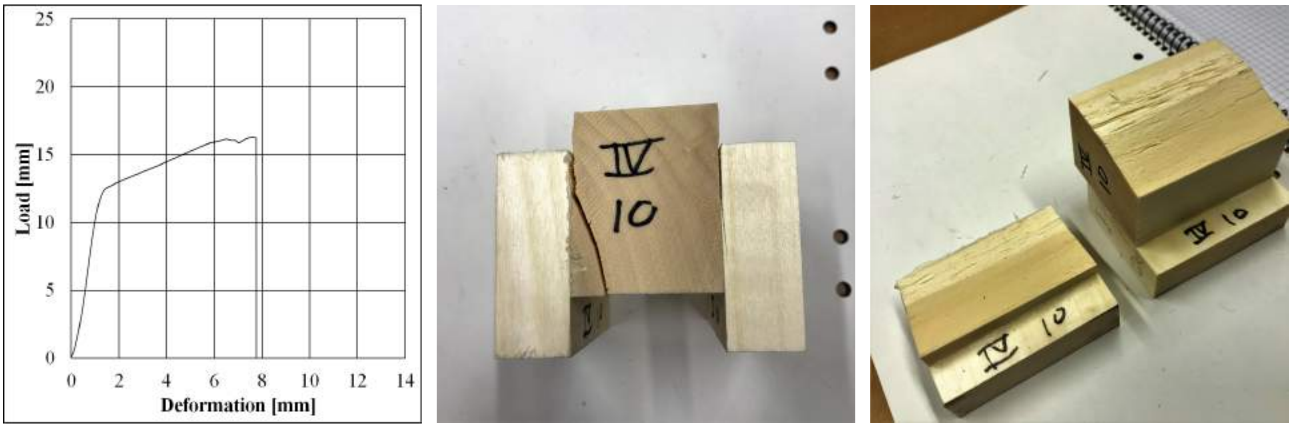

Figure A.32: Specimen IV-9

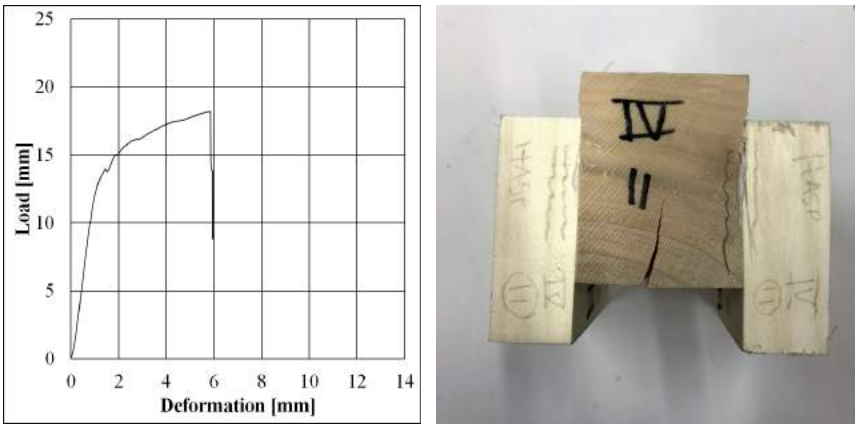

Figure A.33: Specimen IV-10

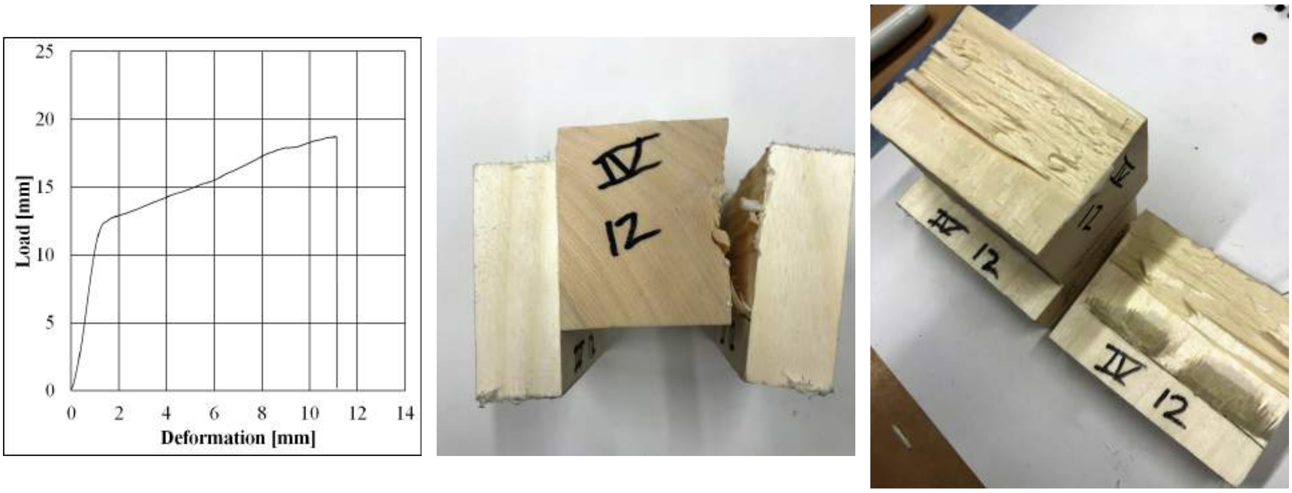

Figure A.34: Specimen IV-11

Figure A.35: Specimen IV-14

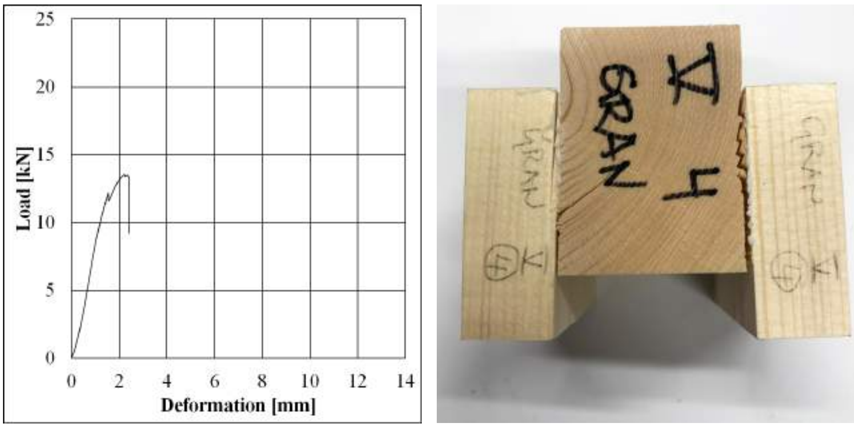

Figure A.36: Specimen V-4

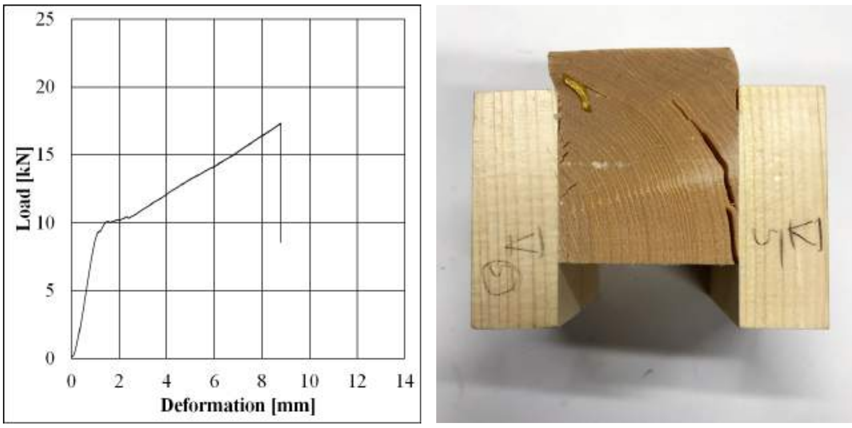

Figure A.37: Specimen V-5

Figure A.38: Specimen V-6

Figure A.39: Specimen V-7

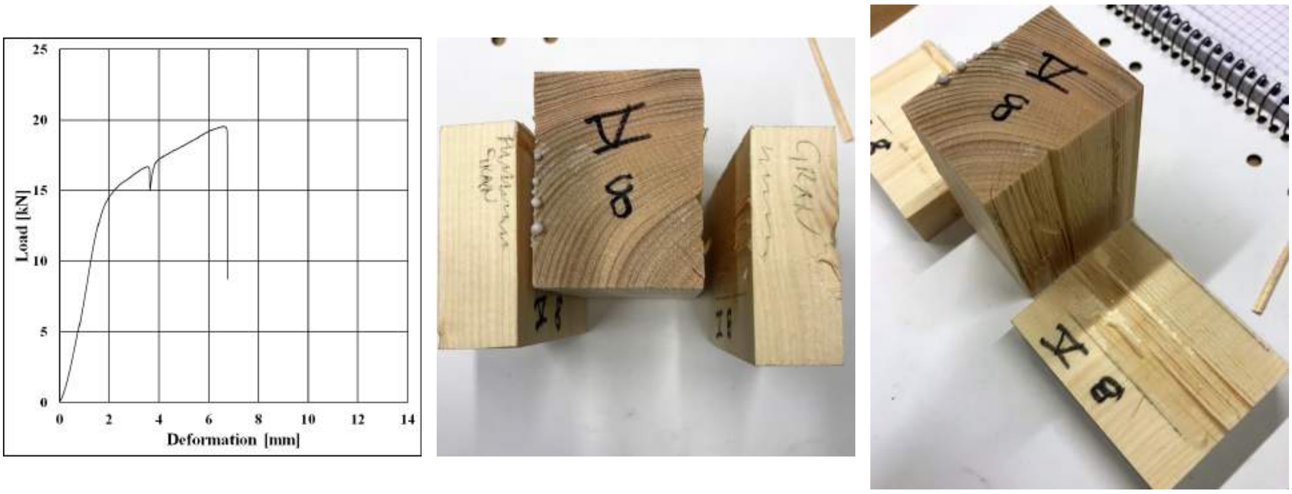

Figure A.40: Specimen V-8

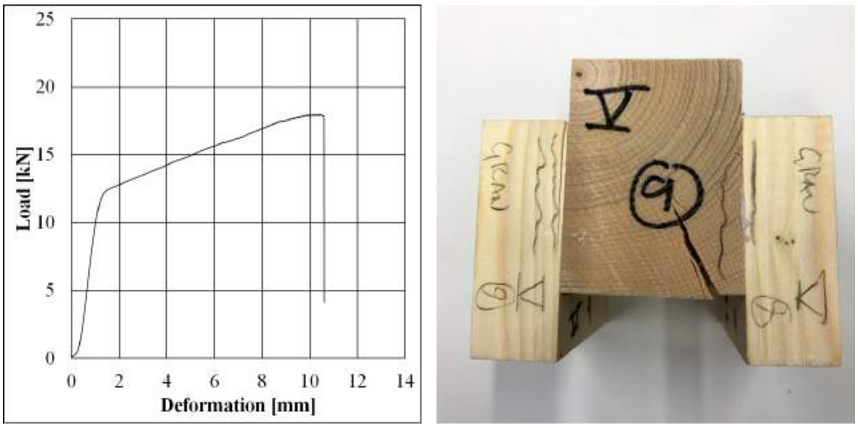

Figure A.41: Specimen V-9

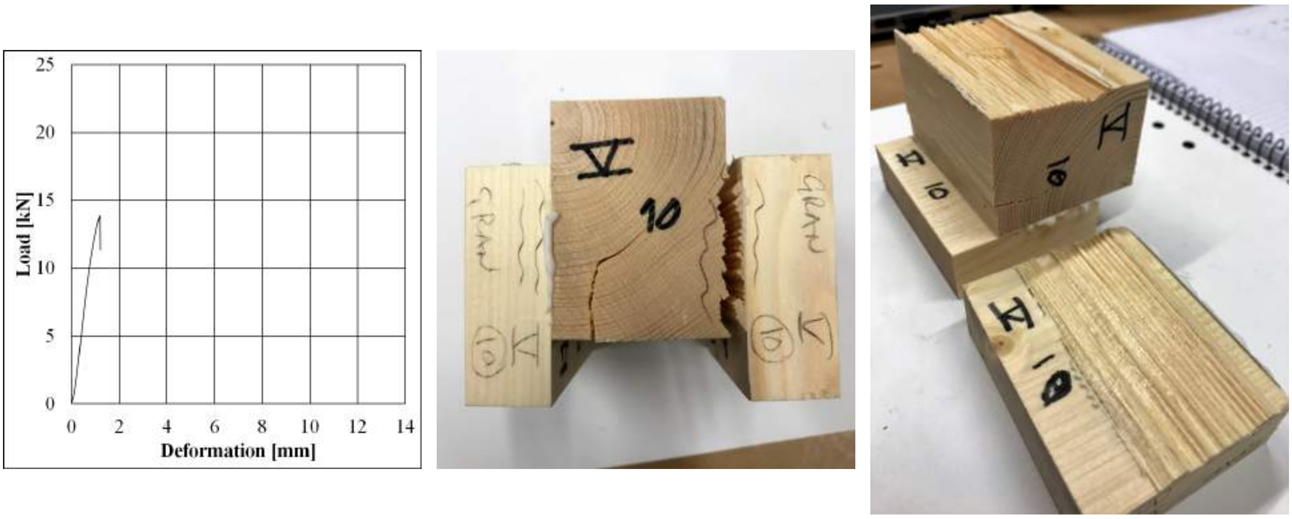

Figure A.42: Specimen V-10

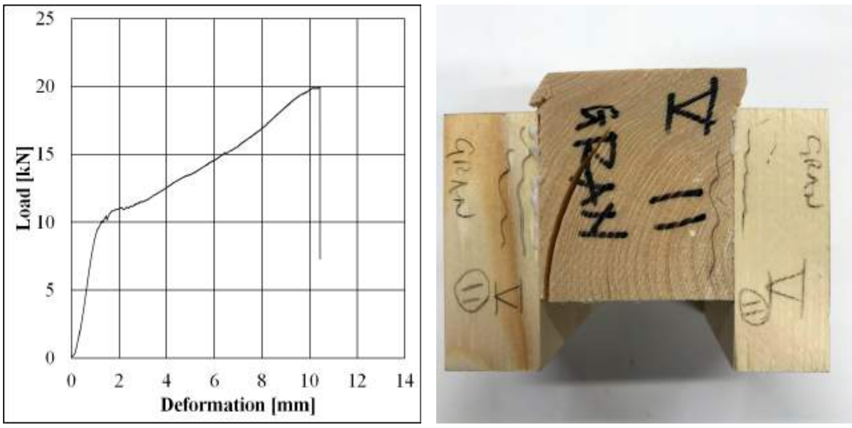

Figure A.43: Specimen V-11

Figure A.44: Specimen V-13

B. Measurement data

Table B.1: Glued area

Specimen	h [mm]	b [mm]	$A = h \cdot b \cdot 2$ [mm^2]
II_13	39.9	69.8	5570
II_7	40.2	70.1	5636
II_5	40.1	70.2	5630
III_3	40.0	69.9	5592
III_8	39.7	70.3	5581
V_2	40.6	69.9	5675
I_1	40.2	69.9	5619
I_6	40.1	70.3	5638
V_1	40.2	69.9	5619
III_13	40.1	69.6	5581
III_6	40.1	70.1	5622
II_8	39.9	69.7	5562
IV_13	40.4	70.1	5664
V_3	40.0	69.9	5592
V_12	40.0	70.0	5600
Mean	40.10	69.98	5612
Standard deviation	0.2138	0.2042	33.39

Table B.2: Specimens mass

	Mass [g]				
	Combination I	**Combination II**	**Combination III**	**Combination IV**	**Combination V**
2018-04-12	181.9	170.0	162.8	138.1	142.2
2018-04-13	183.2	170.8	163.5	138.7	143.3
2018-04-16	184.7	171.8	164.5	139.7	144.3
2018-04-20	184.9	171.8	164.8	139.6	144.6