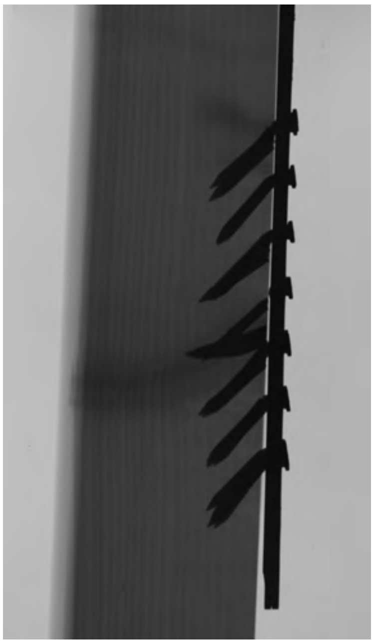
Experimental study on mechanical joints with nail type fasteners

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Experimentell studie på mekaniska spikplåtsförband

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Foreword

This master thesis has been conducted on the Master of Science program in Civil Engineering at Lund University. I would like to thank my supervisor Prof. Roberto Crocetti for his guidance during this thesis. I would also like to thank, in no particular order, Prof. Per Johan Gustafsson, Asst. Prof. Miklós Molnár, Research Eng. Per-Olof Rosenkvist, Prof. Ulf Arne Girhammar and PhD student Thomas Kruglowa.

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Abstract

When timber is used as a building material a connection is required between the elements in order to transfer the load. A typical connection is the steel to timber joint with nail as connectors. These connections can fail in ductile manner, causing the nails to reach their plastic moment capacity, or in brittle manner so called plug shear failure, causing the timber to fail in combined tension and shear failure of the different faces of the plug.

The Eurocode standard for calculating the ductile resistance for one shear plane steel- to timber connections with nail as fasteners is derived from Johansen's theory. It divides five failure modes in two groups. Thick steel plate group and thin steel plate group. The criterion for the groups depends on the thickness of the steel plate used in relation to the fasteners diameter. If a plate is neither thin nor thick according to Eurocode linear interpolation of the resistance is allowed. The plug shear formulation in Eurocode separates the tension and shear resistance in such way that the higher of the two will decide the resistance of the joint.

Seven different ductile nail patterns were designed in order to compare the test results with the Eurocode formulations and a simulation model which is based on the Johansen's yield theory. The joints used both 2.5 and 5mm steel plates with 4mm in diameter nails making the patterns that use 2.5mm plates to count as joints that require interpolation of the resistance according to Eurocode.

After testing all the ductile patterns it was shown that the 2.5mm plate joints had the same, and in some cases, higher failure load than their 5mm joint counterparts. The plastic hinges in the 2.5mm joints were formed at the same location as if a thick steel plate was used even though the 2.5mm plate was closer to the thin plate border of 2mm. Furthermore, nail spacing parallel to the grain did not seem to influence the resistance of the joint even though it should be reduced due to the risk of premature splitting along the line of the nails.

In order to evaluate the current plug shear formulation in Eurocode and to develop an alternative formulation for plug shear failure, six plug shear patterns and three border patterns were designed. After testing all the patterns a nail density limit, where the patterns start to fail in plug shear, was discovered at around 600-700mm^2/nail. The density of the timber seemed to influence the failure load in some patterns when plug shear failure occurred. With help of Matlab a formulation was designed with the data from this thesis test results combined with plug shear data from Johansson's report.

This new formulation includes the density of the timber and the different faces of the assumed timber plug with coefficients in front of them determined from the curve fitting solver function in Matlab.

The stiffness theory which was proposed after observing the experimental test on plug shear joints seemed to capture important parameters in its formulation. It was considered to be a good candidate to predict the failure load when plug shear failure occurs.

Sammanfattning

När trä används som byggnadsmaterial måste de olika elementen förbindas för att lasten ska kunna överföras. Ett typsikt förband är ett stålplåtsförband med spikar som förbindare. Dessa förband kan gå till duktilt brott, vilket resulterar i att spikarnas plastiska momentkapacitet uppnås, eller i sprött brott (träklossbrott), vilket innebär att träet går till brott i kombinerat drag- och skjuvbrott av de olika sidorna av klossen.

Normen i Eurocode för beräkning av den duktila hållfastheten för stålplåtsförband i ett skjuvplan är härlett från Johansens teori. Normen innefattar fem brottmoder uppdelade i två grupper, tjockplåtsgruppen och tunnplåtsgruppen. Kriteriet för grupperna beror på plåtens tjocklek i relation till förbindarens diameter. Om en plåt är varken tjock eller tunn enligt Eurocodes norm är det tillåtet att interpolera linjärt för att få fram hållfastheten. Enligt normen för klossbrott separeras drag- och skjuvhållfastheten så att den högre av de två bestämmer hållfastheten för förbandet.

Sju olika duktila spikmönster skapades för att kunna jämföra provningsresultaten med normerna i Eurocode och en simuleringsmodell baserad på Johansens teori. Förbanden byggdes med både 2.5mm och 5mm tjock stålplåt med 4mm spikdiameter, vilket innebar att förbanden med 2.5mm tjock stålplåt kom att räknas som förband som kräver interpolation enligt normen.

När alla duktila provningar avslutats kunde man se att 2.5mm förbanden hade samma, och i vissa fall högre hållfasthet än deras tvillingförband med 5mm plåttjocklek. Flytlederna i 2.5mm förbanden var utvecklade på samma position som om en tjock plåt hade använts, även fast 2.5mm plåt är närmare den tunna plåtgränsen på mindre eller lika med 2mm. Vidare kunde man se att spikavstånd parallellt fiberriktiningen inte påverkade hållfastheten hos förbanden även fast en reduktion av hållfastheten på grund av risken för spjälkning i träet längst sprikraden förespråkas av Eurocode.

För att kunna utvärdera nuvarande norm i Eurocode med avseende på klossbrott och utveckla en alternativ formulering skapades sex klossbrottsförband och tre gränsförband. Efter att samtliga försök avslutats upptäcktes en gräns för spiktäthet på 600-700mm^2/spik då klossbrott började ske. Träets densitet tycktes påverka brottlasten i vissa av de prövade serierna när klossbrott skedde. Med hjälp av Matlab utvecklades en alternativ formulering för klossbrott som var giltig för förband med spiktäthet 600-700mm^2/spik. Den nya formuleringen är baserad på testresultat från detta examensarbete samt klossbrottsdata från Helena Johanssons rapport.

Den nya formuleringen innehöll träets densitet och de olika delareorna hos den förväntade klossen med koefficienter före dem. Koefficienterna bestämdes med hjälp av en kurvanpassningsmetod i Matlab.

Styvhetsteorin som föreslogs efter att ha observerat testerna på klossbrottsförbanden verkade fånga viktiga parametrar i sin formulering. Den ansågs vara en bra kandidat för att förutsäga brottlasten när klossbrott inträffar.

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1 Introduction

1.1 Background

When timber is used as a building material the different elements, like beams and post, must be connected in order to transfer the load. There are two general types of connections: carpentry joints and mechanical fastener joints. In carpentry joints the force is transferred through friction or direct contact of the joint areas. It is important that these types of joints fit as planned, therefore the manufacture process needs to be precise. Also carpentry joints normally work only in compression. This together with the limitation in their load carrying capacity makes these types of joints not so ideal for more advanced timber structures.

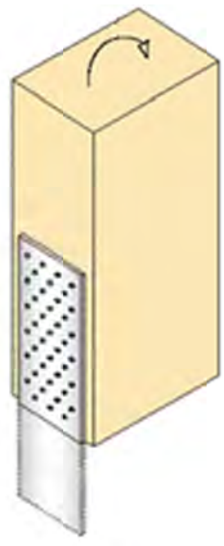
A steel to timber joint with mechanical fasteners is a commonly used connection in more advanced timber structures. One type of fasteners used is nails. A steel to timber joint with nails as connectors must be designed correctly in order to avoid brittle failure in the timber. Brittle failure happens suddenly and its resistance is lower than the ductile failure that happens when the nails fully plasticize.

The two main problems with brittle failure are:

- Brittleness: The fact that the failure is considered brittle. This means that the joint fails suddenly and often without warning.

- Load carrying capacity: The plug shear capacity of the joint is less or equal to the ductile capacity. If the capacity for plug shear is substantially lower than the ductile capacity the joint is neither optimal nor economical.

A better understanding of when plug shear failure occurs would lead to better joint design which would make them safer and more optimal, pleasing both the user and the designer.



An example were a steel to timber joint with nails as fasteners could be used as a ground connection for a timber post.

1.2 Purpose and goal

The purpose of this thesis is to investigate ductile and brittle failure in one shear steel to timber joint. Ductile joints will be tested and the results will be compared with the Johansen's Yield theory and Eurocode formulations. Especially interesting is the formulation in Eurocode when a connection uses a steel plate with thickness in between the thin and thick plate borders.

For the plug shear tests an alternative formulation to the Eurocode theory will be presented based on the test results from this thesis. The results will also be compared with the Eurocode formulation.

1.3 Limitations

- Only one type and strength of timber was used, softwood spruce timber (*Picea Abies*) strength class C30.
- The dimension of the timber was 195x70 mm^2, making it unavailable to perform test on certain nail patterns.
- The hole spacing of the steel plate used was standard, 40mm parallel to the grain and 20mm perpendicular to the grain limiting the nail placement.
- The joints were tested in tension parallel to the grain and only in short-term loading.

1.4 Method

To gain more information about ductile and brittle failure in timber joints a literature study was undertaken. After the aim of the thesis had been decided, softwood timber with strength class C30 was ordered. The timber was cut the same day it arrived. A standard template for all tests was made, see appendix E. Before each test the timber element of the joint was weighted in order to measure its density, and moisture readings were taken before nailing the steel plate in place. Two identical patterns were nailed on each side of the timber element. When the joint was complete a reference mark was made at the top of each steel plate so that deformation readings could be made when one of the two sides had failed. The joint was then inserted in a servo hydraulic testing machine and loaded in tension parallel to the grain until failure occurred in either the top or bottom connection. Deformation readings were taken and failure load was registered. The software used to monitor the tests created a log file with force displacement data.

If the joint failed with ductile failure the nails were removed from the steel plate and examined. If plug shear failure occurred, the whole plug including the steel plate and nails where weighted. The weight of the steel plate and nails was removed from the total weight and left was only the weight of the timber plug. When the weight of the plug was known and with information of the timbers density, the volume was calculated. The length and width of the plug was measured, and together with the volume, a mean plug depth was estimated.

Load displacement graphs were plotted with the information given from the tests. With all test data gathered an analysis was made which was mainly divided in two parts, the ductile part and the plug shear part.

2 Theory

2.1 Mechanical timber joints

When using timber as a building material, the joints between the elements will mainly be the part that decides the design value. There are two general types of joints, carpentry joints and mechanical joints made with different types of fasteners.

Mechanical joints can be divided into two types of groups depending on the fastener type. Joints with dowels as fasteners are one of the most commonly used groups. The dowel types included in this group are staples, nails, bolts and screws. The other group uses fasteners like split rings, shear-plates and punched metal plates.

For mechanical timber joints with nailed steel plates, also referred to as steel to timber joints, different type of nails can be used. The most common types are round wire nails but there are other types as well, like helically threaded nails, annular ringed shank nails and machine driven nails.
When inserting the nails, predrilling might be required to avoid splitting of the wood. Splitting can occur if the distance between the nails is insufficient, the density of the wood is high or a combination of both [1].

Figure 1: Mechanical steel to timber joint with nail type fasteners.

There are different types of failure for a mechanical timber joint with dowel type fasteners. For steel to timber joints using nails as fasteners all failure types in fig 2 are possible except e) because the nail diameter is too small to create two shear planes, see fig. 2 [5].

a) Plug shear failure – Brittle failure
b) Cracks along the line of nails – Brittle failure
c) Tensile failure – Brittle failure
d) Yielding of the nails – Ductile failure
e) Row shear – Brittle failure
f) Embedding failure in timber – Semi ductile

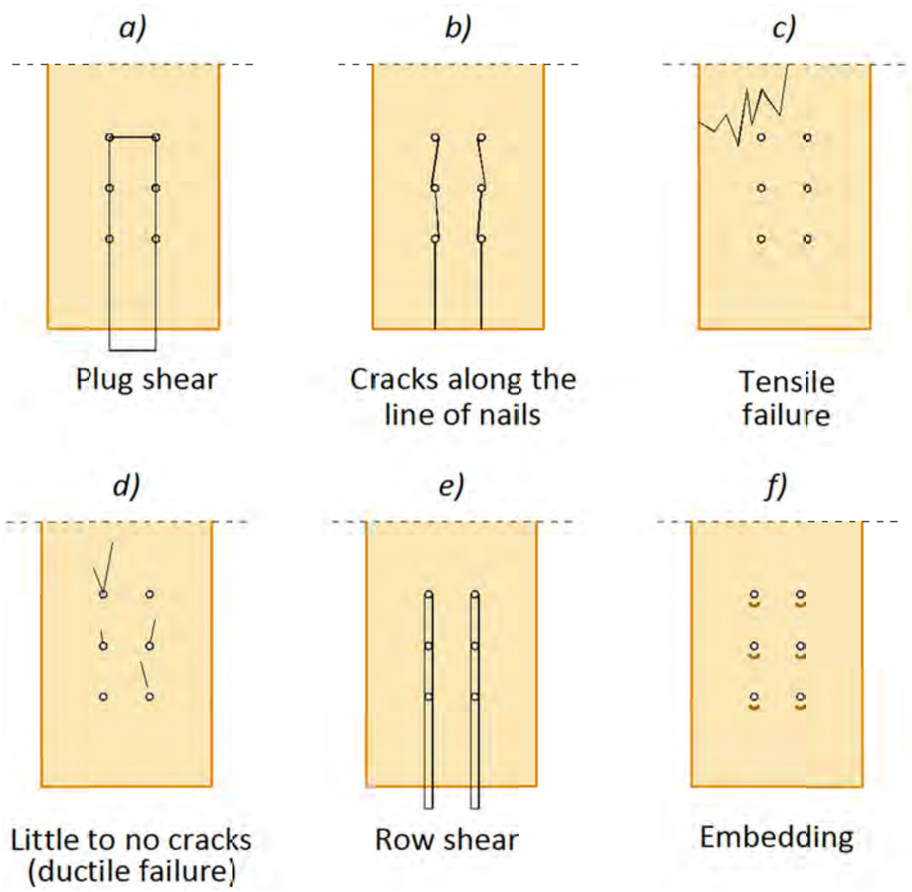


Figure 2: Failure types of a mechanical timber joint with dowel type fastener when loaded parallel to the grain.

2.2 Johansen's yield theory

In 1949 K.W. Johansen published a report were he described the possible failure modes for timber to timber and steel to timber joints using dowel type fasteners. The equations presented by him were used to predict the failure mode that would occur in the joint [1]. In Eurocode 5 the equations used to calculate the design resistance for a steel to timber joint with dowel type fasteners are the Johansen's equations with some modifications applied to some of them [2].

For single shear steel to timber joints using nails as fasteners five different failure modes can occur. The resistance of the joint depends on the diameter of the dowel, the thickness of the timber member, the embedment strength of the wood and the plastic moment of the nail. The failure modes are divided into two groups depending on the plate's thickness, see fig. 3.

A thick plate is by definition a plate with thickness equal or greater than the diameter of the nail. In this setup the plate acts as a fix support for the nail allowing the formation of a plastic hinge in the steel timber interface. Three failure modes can occur, see fig. 3.

Failure mode a) Embedment failure in the timber. The timbers embedment strength, which is derived from the timbers density, will decide the failure load. The resistance is given by the following equation:

$$R_a = f_h t_1 d \; [N]$$

where:
t_1 is the nails penetration length
d is the diameter of the nail
f_h is the embedment strength of the wood

Failure mode d) One plastic hinge formed in the nail at the steel timber interface. The resistance is given by the following equation:

$$R_d = f_h t_1 d * \left(\sqrt{2 + \frac{4M_y}{f_h d t_1^2}} - 1 \right) \; [N]$$

where:
M_y is the yield moment of the nail

Failure mode e) Two plastic hinges formed in the nail, one at the steel timber interface and one inside the timber. The resistance is given by the following equation:

$$R_e = 2\sqrt{M_y f_h d} \; [N]$$

A thin plate is by definition a plate with thickness less than half the size of the diameter of the nail. In this setup a plastic hinge cannot form in the steel timber interface because the nail will rotate in the hole. Two failure modes can occur, see fig. 3.

Failure mode a) Embedment failure in the timber. The resistance is given by the following equation:

$$R_a = 0{,}4 * f_h t_1 d \ [N]$$

Failure mode b) One plastic hinge formed in the nail inside the timber. The resistance is given by the following equation:

$$R_b = \sqrt{2 * M_y f_h d} \ [N]$$

When a thick plate is used the minimum value of the thick plate equations, R_c, R_d, and R_e will decide the resistance for the connection and failure mode. For thin plates the minimum value of the thin plate equations, R_a and R_b will decide the resistance for the connection and failure mode [1].

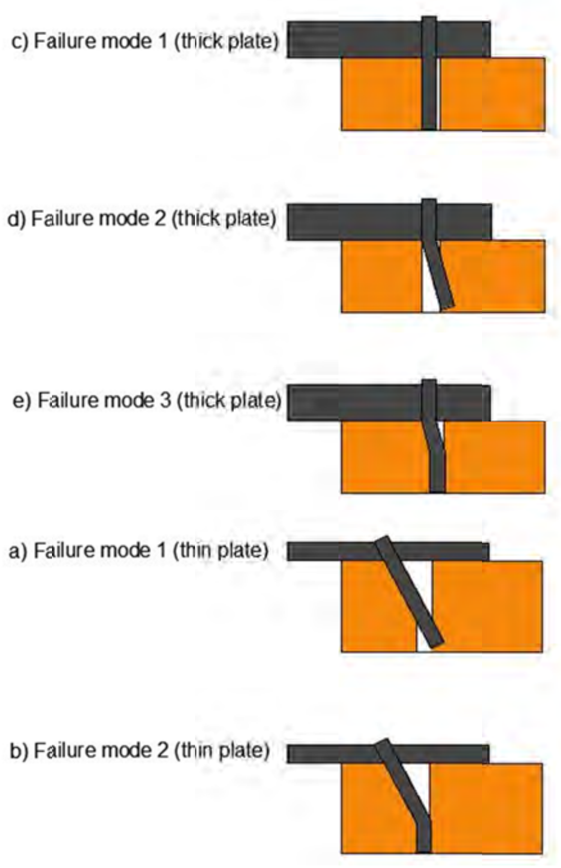


Figure 3: Thin failure modes:
a) Failure mode 1 - Embedment failure in the wood
b) Failure mode 2 - One plastic hinge formed in nail.
Thick failure modes:
c) Failure mode 1 - Embedment failure in the wood
d) Failure mode 2 - One plastic hinge formed in nail
e) Failure mode 3- Two plastic hinges formed in nail.

2.3 Eurocode 5 - Ductile failure modes

Eurocode 5 uses formulations which are derived from Johansen's yield theory. As in Johansen's case there are five different failure modes in two groups depending on the thickness of the plate in relation to the nails diameter, see fig. 3. The strength of a nailed connection is related to the yield moment of the nail and the embedment strength of the wood. The characteristic embedment strength, $f_{h,k}$ of the wood is calculated from the following expressions [2]:

Without predrilled holes:

$$f_{h,k} = 0{,}082\rho_k d^{-0,3} \ [N/mm^2]$$

With predrilled holes:

$$f_{h,k} = 0{,}082(1 - 0{,}01d)\rho_k \ \ [N/mm^2]$$

where:

ρ_k is the characteristic density of the timber [kg/m^3]
d is the diameter of the nail [mm]

The characteristic yield moment, M_{yRk} of a nail with a minimum tensile strength of 600 N/mm^2 is calculated from the following expression [2]:

$$M_{yRk} = 0{,}3 f_u d^{2,6}$$

where:

f_u is the tensile strength of the nail [N/mm^2]
d is the diameter of the nail [mm]

The thickness of the steel plate used, compared to the diameter of the nail will determine what formulations are used. A thin plate has the thickness less or equal to half the diameter of the nail and will act as a pinned support, while a thick plate has the thickness more or equal to the diameter of the nail and will act as a fixed support [5].

If a thin plate is used, that is if $t_{plate} \leq 0{,}5 d_{nail}$ the formulations state that only two failure modes can occur, failure mode I and II. The minimum value of the following two expressions will be the designing value of the joint [2].

$$R_{thin,I} = 0{,}4 f_{h,k} t_1 d \ [N]$$
$$R_{thin,II} = 1{,}15\sqrt{2 * M_{yRk} f_{h,k} d} + \frac{F_{ax,Rk}}{4} \ [N]$$

where:

t_1 is the penetration depth of the nail [mm]
d is the diameter of the nail [mm]
$\frac{F_{ax,Rk}}{4}$ is the axial resistance of the fastener, rope effect [N]

For nails, the axial resistance depends on the surface roughness along the nails ($f_{ax,k}$) and the anchorage capacity of the nails ($f_{head,k}$). Only 15% of the rope effect is allowed to take into account when using nails as fasteners [2]. These can be calculated using the following expression [5]:

$$f_{ax,k} = 20 * 10^{-6} p_k^2 \; [N/mm^2]$$
$$f_{head,k} = 70 * 10^{-6} p_k^2 \; [N/mm^2]$$

For non smooth nails the axial resistance is obtained through the following expression [5]:

$$F_{ax,Rk} = min \begin{cases} f_{ax,k} * d * t_1 \; [N] \\ f_{head} * d_{head}^2 \; [N] \end{cases}$$

where:
d_{head}^2 is the diameter of the nail head [mm]
d is the diameter of the nail [mm]
t_1 is the penetration depth of the nail [mm]

The contribution of the rope effect is usually very small and can often be neglected.

For a thick plate, $t_{plate} > d_{nail}$ three failure modes can occur and the design value is the minimum of the following expressions [2].

$$R_{thick,I} = f_{h,k} t_1 d \; [N]$$

$$R_{thick,II} = f_{h,k} t_1 d * \left(\sqrt{2 + \frac{4M_{yRk}}{f_{h,k} d t_1^2}} - 1 \right) + \frac{F_{ax,Rk}}{4} \; [N]$$

$$R_{thick,III} = 2{,}3 \sqrt{M_{yRk} f_{h,k} d} + \frac{F_{ax,Rk}}{4} \; [N]$$

If a plate is used that is by definition in between a thin and thick plate, linear interpolation of the resistances is allowed.

The equations given by the norm in Eurocode correspond to the resistance of a one nail joint. In a connection when nails are placed in the same row with insufficient spacing a reduction of the capacity may be applied due to the risk of splitting [2].

$$R_{red} = n_{eff} * R \; [N]$$

where:
R is the resistance for one nail
n_{eff} is a reduction factor for multiple nails in a row
$n_{eff} = n^{k_{eff}}$
n is the real number of nails in a row
k_{eff} is obtained through table 1

Table 1: Values of k_{ef}, a_1 is the distance between the nails parallel to the grain.

Spacing[a]	k_{ef}	
	Not predrilled	Predrilled
$a_1 \geq 14d$	1,0	1,0
$a_1 = 10d$	0,85	0,85
$a_1 = 7d$	0,7	0,7
$a_1 = 4d$	-	0,5
[a] For intermediate spacings, linear interpolation of k_{ef} is permitted		

Splitting failure is when the timber cracks open in an entire nail row. Because the timber fails before the nails plasticize, the failure type is brittle and should be avoided. Minimum spacing distances according to Eurocode 5 are presented in table 2. For nailed steel to timber joints the values for table 2 are valid for the edge and end distances, but the nail spacing can be multiplied by a factor of 0,7. The angle α in table 2 is defined in fig. 4.

Table 2: Minimum spacing, edge and end distances for nails in steel to timber joints.

Spacing or distance (see Figure 8.7)	Angle α	Minimum spacing or end/edge distance		
		without predrilled holes		with predrilled holes
		$\rho_k \leq 420$ kg/m^3	420 kg/m$^3 < \rho_k \leq 500$ kg/m^3	
Spacing a_1 (parallel to grain)	$0^\circ \leq \alpha \leq 360^\circ$	$d < 5$ mm: $(5+5\lvert\cos\alpha\rvert)\,d$ $d \geq 5$ mm: $(5+7\lvert\cos\alpha\rvert)\,d$	$(7+8\lvert\cos\alpha\rvert)\,d$	$(4+\lvert\cos\alpha\rvert)\,d$
Spacing a_2 (perpendicular to grain)	$0^\circ \leq \alpha \leq 360^\circ$	$5d$	$7d$	$(3+\lvert\sin\alpha\rvert)\,d$
Distance $a_{3,t}$ (loaded end)	$-90^\circ \leq \alpha \leq 90^\circ$	$(10+5\cos\alpha)\,d$	$(15+5\cos\alpha)\,d$	$(7+5\cos\alpha)\,d$
Distance $a_{3,c}$ (unloaded end)	$90^\circ \leq \alpha \leq 270^\circ$	$10d$	$15d$	$7d$
Distance $a_{4,t}$ (loaded edge)	$0^\circ \leq \alpha \leq 180^\circ$	$d < 5$ mm: $(5+2\sin\alpha)\,d$ $d \geq 5$ mm: $(5+5\sin\alpha)\,d$	$d < 5$ mm: $(7+2\sin\alpha)\,d$ $d \geq 5$ mm: $(7+5\sin\alpha)\,d$	$d < 5$ mm: $(3+2\sin\alpha)\,d$ $d \geq 5$ mm: $(3+4\sin\alpha)\,d$
Distance $a_{4,c}$ (unloaded edge)	$180^\circ \leq \alpha \leq 360^\circ$	$5d$	$7d$	$3d$

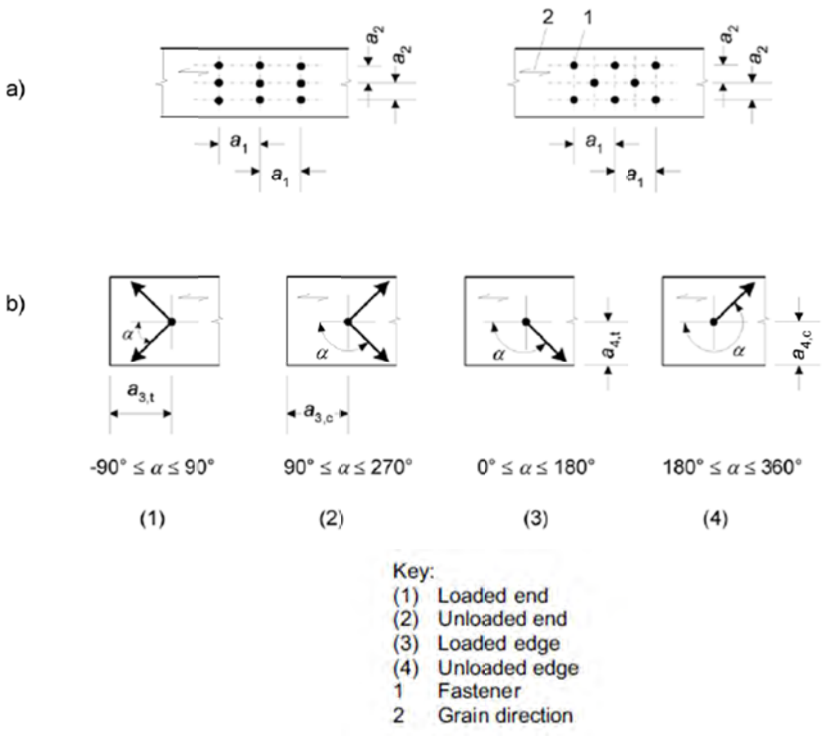


Figure 4: a) Nail spacing parallel and perpendicular to the grain. b) Edge and end distances, α is the angle between grain direction and force. 1) Loaded end 2) Unloaded end 3) Loaded edge 4) Unloaded edge.

2.4 Plug shear failure

Plug shear failure occurs when the timber part of the joint fails before the full capacities of the nails are used. The timber piece will be torn off in a rectangular shape. The failure type is brittle and the parameters involved in calculating the resistance is the timber's shear and tension strength. Because of the geometry of the plug, different faces of the timber will contribute to the total resistance. The assumed stress distribution is shown in fig. 5 and the faces involved in fig. 6.

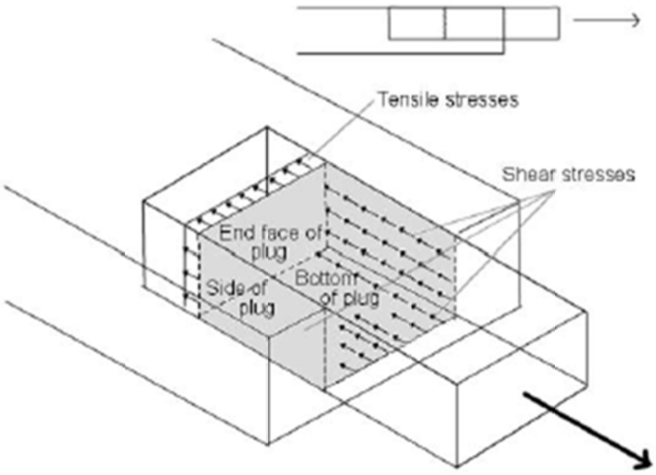


Figure 5: Stress distribution on the timber (Johansson 2004).

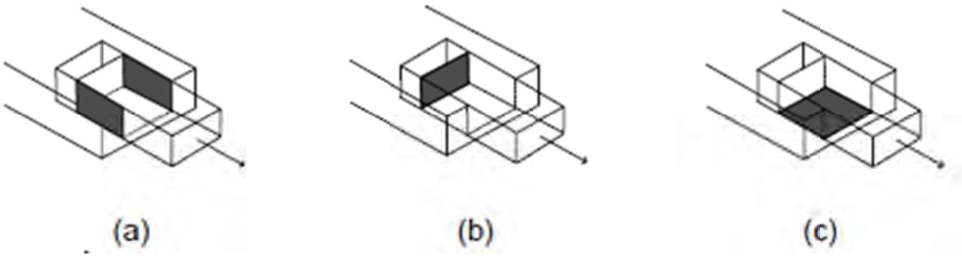


Figure 6: Side shear areas (a), Tension area (b), and Bottom shear area (c) (Johansson 2004).

Plug shear failure will occur when the timber's resistance is lower than the resistance corresponding to one of the ductile failure modes according to Eurocode 5. Because of the brittleness in plug shear failure the load displacement graph will resemble fig. 7.

There are different theories that estimate the resistance of plug shear failure, some of them are presented below.

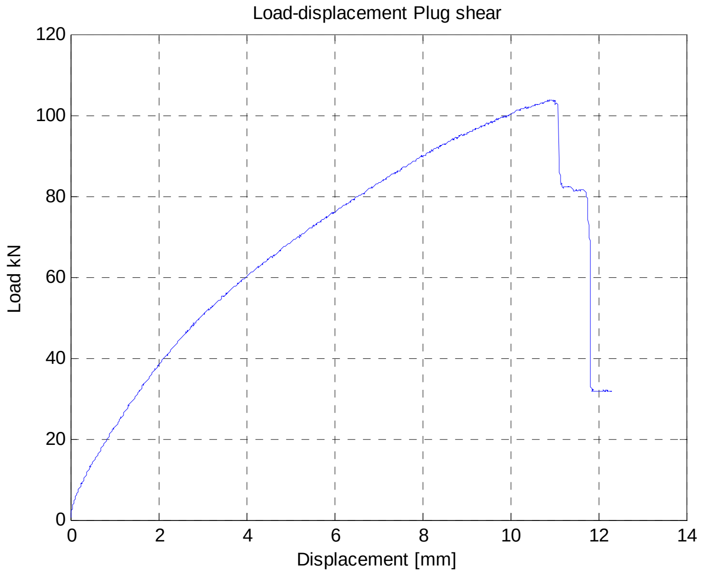


Figure 7: Typical plug shear load displacement curve.

2.4.1 Foschi and Longworth

Early research has been carried out on this type of failure by Foschi and Longworth (1975). They suggested the following expression when calculating the resistance for plug shear failure.

$$R_{ps} = min\begin{cases} \dfrac{f_t h(b - 2d_y)}{K_t \beta_t a_t \gamma_h} \\ \dfrac{2 f_v h l}{K_s \beta_s \gamma_h} \end{cases}$$

where:

$b - 2d_y$ is the width of the joint
h is the penetration depth of the nail
l is the distance between the furthest away nail and the end of the joint
f_{t0} is the tensile strength parallel to grain of the timber
f_v is the shear strength of the timber

K, β, α and γ are empirically derived factors that take into account: number of nail rows and columns, nail spacing, timber thickness and penetration depth.

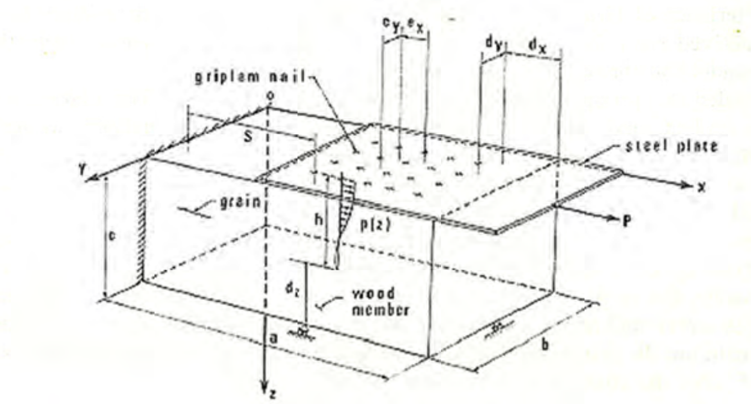


Figure 8: Geometrical variables according to Foschi and Longworth.

As seen in the expression above the tensile and shear contributions are separated. That means if either one of the areas fail first the other one does not contribute to the resistance. Also, the bottom shear area is not taken into account at all only the side shear area. The plug formed is also assumed to have the depth equal to the penetration length of the nails [4].

2.4.2 Eurocode 5 plug shear formulation

In Eurocode 5, the characteristic plug shear resistance for a steel to timber joint, is given by the following formulation:

$$F_{ps,Rk} = max\begin{cases} 0{,}7A_{net,v}f_{v,k} \\ 1{,}5A_{net,t}f_{t,0,k} \end{cases}$$

where:

$A_{net,v}$ is the net shear area of the plug, both side and bottom area excluding the area of the nails along the sides fracture line
$A_{net,t}$ is the net tension area of the plug excluding the area of the nails along the tension fracture line

$f_{v,k}$ is the characteristic shear strength of the timber
$f_{t,0,k}$ is the characteristic tension strength of the timber

$$A_{\text{net, t}} = L_{\text{net, t}} \cdot t_1$$
$$L_{\text{net,t}} = \sum_i l_{t,i}$$
$$A_{\text{net,v}} = \frac{L_{\text{net,v}}}{2} \cdot \left(L_{\text{net,v}} + 2 \cdot t_{\text{ef}}\right)$$
$$L_{\text{net,v}} = \sum_i l_{v,i}$$

$l_{t,i}$ and $l_{v,i}$ are the length along the fracture line excluding the nails diameter, see fig. 9.
t_{ef} is the effective depth of the plug depending of the ductile failure mode of the nail, see fig 3.

for thin plates:

$$t_{ef} = \begin{cases} 0,4 \;\; t_1 & \text{(a)} \\ 1,4\sqrt{\dfrac{M_{y,Rk}}{f_{h,k}\; d}} & \text{(b)} \end{cases}$$

for thick plates:

$$t_{ef} = \begin{cases} 2\sqrt{\dfrac{M_{y,Rk}}{f_{h,k}\; d}} & \text{(d)} \\ t_1\left[\sqrt{2+\dfrac{M_{y,Rk}}{f_{h,k}\, d\, t_1^2}}-1\right] & \text{(c)} \end{cases}$$

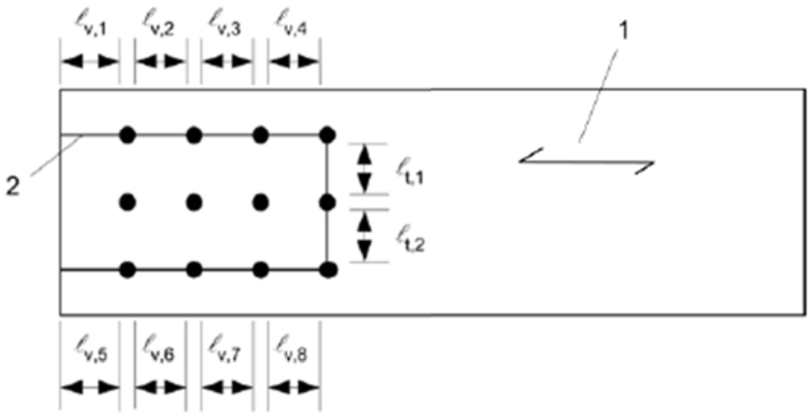


Figure 9: Geometrical variables for plug shear failure according to Eurocode 5, 1 marks the grain direction, 2 marks the fracture line.

The factors 1.5 and 0.7 in front of the expressions are derived empirically. The tensile expression is multiplied by 1.5 because it's less probable to have local defects in a small area compared to the whole timber element. The shear expression is lowered because of a volume effect that affects the shear strength negatively when the shear area increases [5].

2.4.3 The stiffness theory

This theory was proposed after observing the experimental tests performed in this thesis. The scenario is explained in chapter 4.3.

The plug shear tests observation led to the assumption that the load was taken unevenly between the sides, bottom and tension areas due to different stiffness of these parts. With knowledge of the materials strength properties, E-modulus, shear modulus and area of the different faces of the plug, the expected failure load for plug shear failure can now be formulated.

Assuming that the tension area fails first the load taken by that face is given by the following expression:

$$\alpha = \frac{K_t}{K_{tot}}$$
$$K_t = E * A_t$$
$$K_{tot} = (A_s + A_b) * G + E * A_t$$

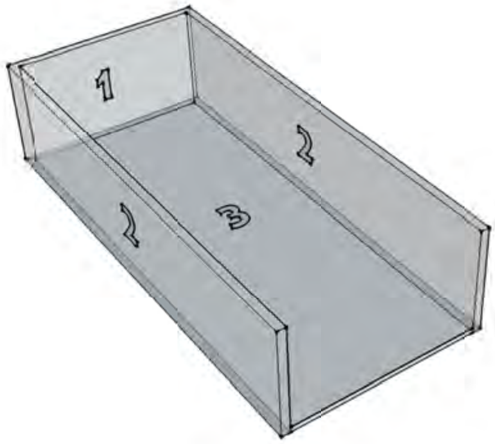
where:

α is the load taken in percent by the tension area
G is the shear modulus of the timber
E is the elasticity modulus of the timber
A_s is the side shear area
A_b is the bottom shear area
A_t is the tension area

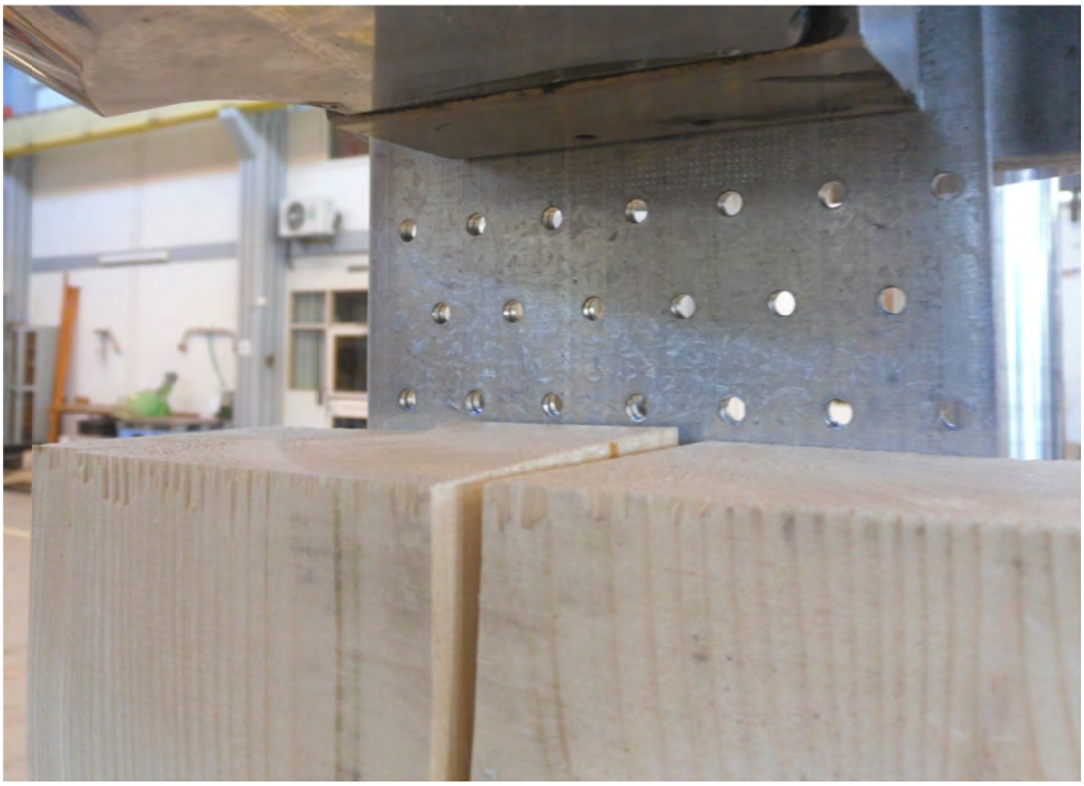
K_t is the tension stiffness
K_{tot} is the total stiffness for all faces

Since the load is taken unevenly by the different faces the resistance for the tension side should be more than just tension area multiplied by the tension strength. More exactly, tension area multiplied by tension strength multiplied by the inverse of its load taken. This leads to the following plug shear resistance formulation, referred to as the resistance for plug shear failure according to the stiffness theory.

$$R_{ST} = \frac{1}{\alpha} * f_t * A_t$$



1: Tension area, 2: Side area, 3: Bottom area.



Initial tension failure in one of the plug shear tests performed.

3 Test setup

In order to evaluate the current theories concerning brittle and ductile failure in steel to timber joints, full size tests were conducted at LTH's lab. The joints were tested in tension parallel to the grain and in short-term loading. Eight ductile series and nine plug shear series were tested. A total of 101 tests were performed in this testing program.

The tests were conducted using a MTS servo hydraulic testing machine with a maximum load of 500kN. The loading speeds were 2mm/min for ductile joints and 1mm/min for joints that were expected to fail in plug shear failure. Each specimen was built so that the timber element had the same nail pattern on both edges. The steel plates were then loaded on both sides until the weakest connection failed.

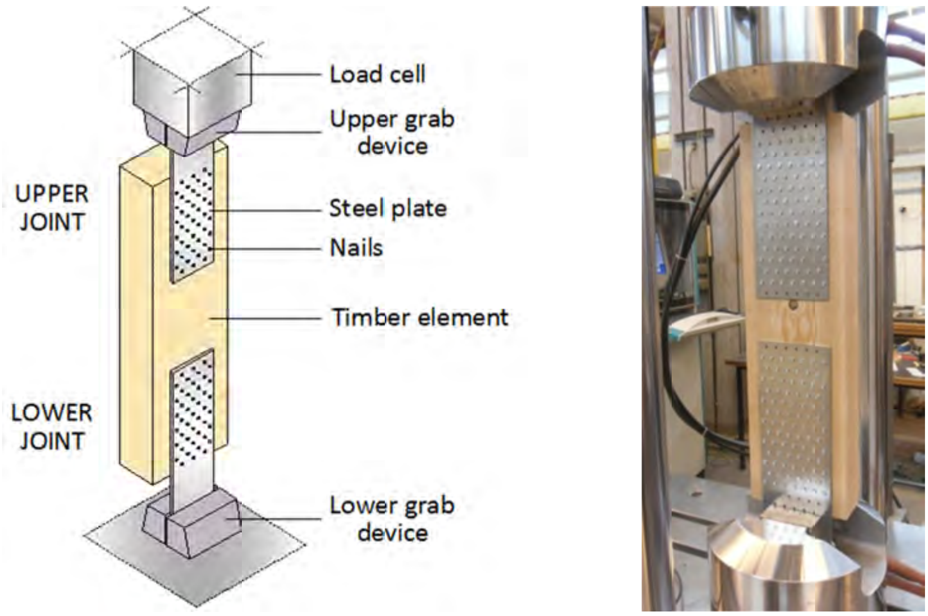


Figure 10: Test setup.

Connection materials

Gunnebo anchor nails were used as connectors with 4mm in diameter and length 40 and 60mm. The nails were tested in the lab in order to determine their yield strength.

The timber used was softwood strength class C30. The specimens varied in length from 300 to 900 mm with a cross section of 70 x 195 mm^2.

Steel plates S235 with a thickness of 2.5mm were used. Some tests used two steel plates overlapped creating a 5mm plate.

Density measurements

Before testing, each timber element was weighted and with knowledge of the volume the density could calculated. The density acquired in this way is a mean density for the entire element, when calculating the resistance according to Eurocode 5 the embedment strength is related to the density of the wood under each nail. Therefore the more nails a ductile connection has the smaller this problem gets.

Nail yield strength measurements

The purpose of these tests was to have more accurate data when running the simulation model. The yield moment M_y and the yield strength f_y can be calculated through the following expression:

$$M_y = \frac{F_y * L}{4} = \frac{d^3 * f_y}{6}$$

where:

F_y is the yield load
f_y is the yield strength
L is the distance between the supports
d is the diameter of the nail

For the 40mm nails the support distance was L_{40}=26mm, and for the 60mm nails L_{60}=45mm. The results from the nail bending tests can be found in appendix C.

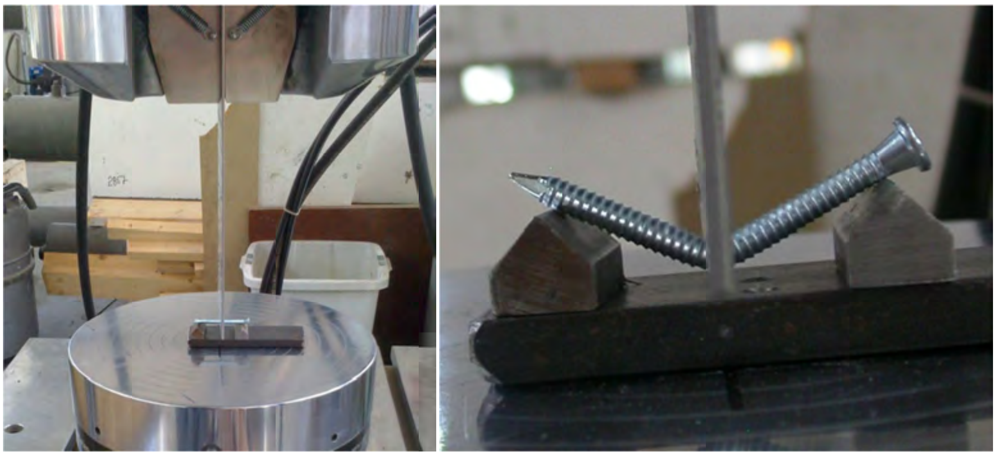


Figure 11: Nail test before and after.

Moisture content measurements

The moisture content in all timber elements was measured using an electric hygrometer. Three points were measured and the final value was chosen as a mean value of the three points. The moisture readings varied from 9 to 11% in all specimens.

X-ray camera

With the use of an X-ray camera provided by Thomas Kruglowa (PhD student at Chalmers University of technology), images were taken of the test specimens. X-ray images were taken before, during and after testing the specimens. Both ductile and plug shear joints were examined.

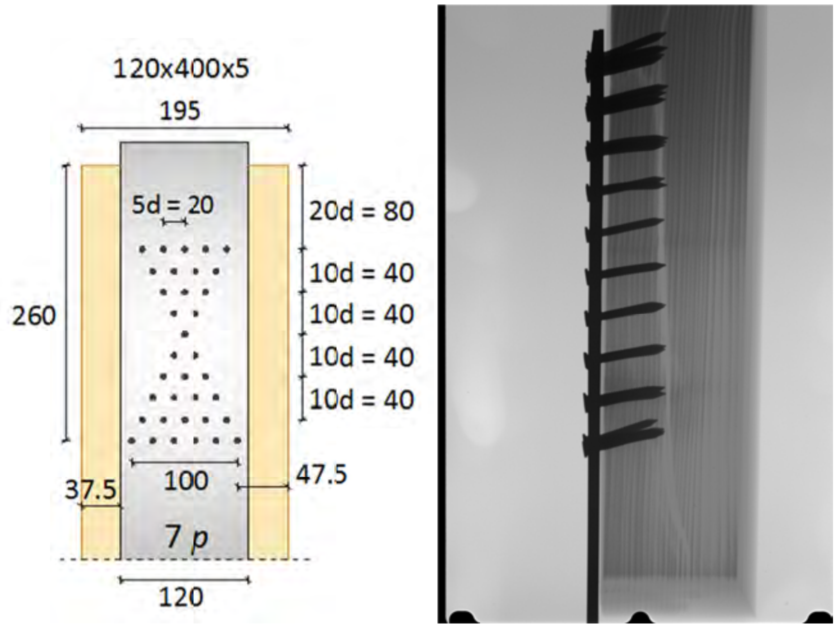


Figure 12: Serie 7p, plug shear line formed at the tip of the nails as a thick white line.

4 Result and Analysis

This chapter will present the test results from the ductile and plug shear patterns. The ductile results will be compared with the Eurocode 5 standard and Johansen's yield theory. The plug shear results will be compared with the Eurocode formulation and some new theories.

4.1 Matlab joint simulation model

In order to compare the test results with the Johansen's yield theory a simulation model was written in Matlab. The main idea of the program is to simulate a one nail connection with all parameters fixed, except the density of the timber and the yield strength of the nails which will be randomly selected from a given interval. The range of the density that was used was 349-536 kg/m^3, this range was determined after measuring the density for all the specimens. When deciding the range of the yield strength the information from the nail bending tests was used, see appendix C. The range was 792-939 MPa. Information about the joints nail penetration length, nail diameter, plate thickness and number of simulations must also be entered.

After entering all the necessary joint information the program loops n times, were n is the number of simulations entered. Each loop will create a new joint with a density and yield strength value selected from the inputted ranges. Inside the loop the program will use Johansen's equations to determine the resistance of joint. Information of the joint's failure mode, failure load, embedment strength, plastic moment capacity etc. will be stored in an excel file.

Resistance	Failure Mode	Density	Fh	Fy	Mpl		FM Thick	FM Thin		FM 1	FM 2	FM 3
1,76	2	447,9	24,2	998,2	10647,9		0,00	0,00		3,20	1,76	2,34
1,54	2	387,7	21,0	897,6	9574,0		0,00	0,00		2,77	1,54	2,06
1,91	2	530,2	28,7	777,0	8288,4		0,00	0,00		3,79	1,91	2,24
2,02	2	550,8	29,8	894,3	9538,9		0,00	0,00		3,93	2,02	2,45
1,39	2	346,6	18,8	846,6	9030,1		0,00	0,00		2,48	1,39	1,89
2,00	2	537,8	29,1	919,5	9808,1		0,00	0,00		3,84	2,00	2,46
1,83	2	490,7	26,5	853,9	9108,3		0,00	0,00		3,50	1,83	2,26
1,67	2	434,0	23,5	875,7	9340,9		0,00	0,00		3,10	1,67	2,15
1,54	2	394,9	21,4	846,5	9029,2		0,00	0,00		2,82	1,54	2,02
1,39	2	344,4	18,6	862,9	9204,1		0,00	0,00		2,46	1,39	1,91
1,36	2	352,3	19,1	731,3	7800,8		0,00	0,00		2,52	1,36	1,77
1,78	2	503,9	27,3	649,5	6928,0		0,00	0,00		3,60	1,78	2,00
1,63	2	422,3	22,8	859,2	9164,3		0,00	0,00		3,02	1,63	2,10
1,45	2	345,9	18,7	990,8	10568,8		0,00	0,00		2,47	1,45	2,05
1,62	2	432,4	23,4	782,1	8342,0		0,00	0,00		3,09	1,62	2,03
1,86	2	497,9	26,9	883,9	9428,4		0,00	0,00		3,56	1,86	2,32
1,63	2	448,5	24,3	697,0	7435,1		0,00	0,00		3,20	1,63	1,95
1,74	2	471,9	25,5	784,1	8363,5		0,00	0,00		3,37	1,74	2,13
1,83	2	490,1	26,5	864,0	9216,0		0,00	0,00		3,50	1,83	2,27

Figure 13: Example output with the 20 first simulations shown.

This information can be used to determine the mean and characteristic value of all the simulations, which can then be compared to the test results. If a joint is created with a 2,5mm steel plate, so that calculating the resistance needs to be linear interpolated between the thick and thin plate formulations, the program will print out the individual thick and thin plate resistances in addition to the interpolated value. These individual resistances can be valuable to have when comparing simulated and test results. After all simulations are done a graph will be created, see fig. 14. The simulation model does not take into account the rope effect since its contribution is often small. The simulation results for the different series are shown in appendix D.

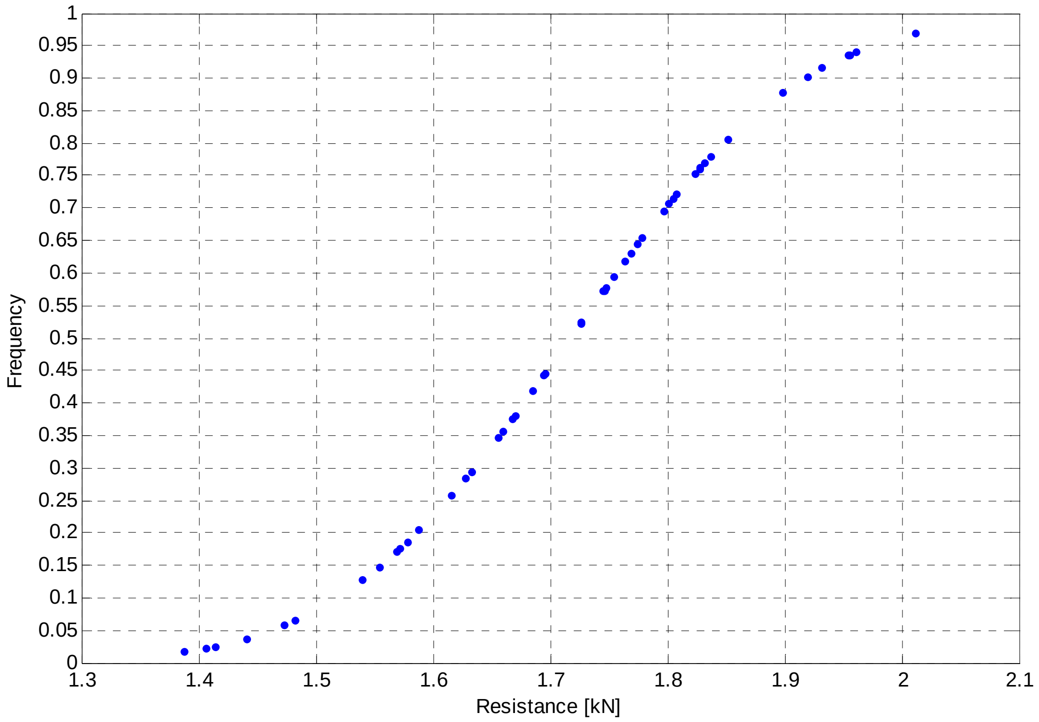


Figure 14: Plot of the resistance, each point represents a joint with a unique density and yield strength.

4.2 Results – Ductile failure

The testing series below will be presented in the following way.

X-Y-nZ

where Xd denotes the series name
Y is the plate thickness used in mm
Z is the nail length used in mm

For example 2d-2.5-n40 means that the series name was 2d and the joints were build with 2,5mm steel plate and 40mm nails.

Series 2d

2d-2.5-n40
Six specimens were tested with this setup. Five of them failed in ductile manner and one failed in brittle (splitting). For the ductile failures the observed failure mode was 2, mode d) fig. 3. The results from the tests are given in table 3.

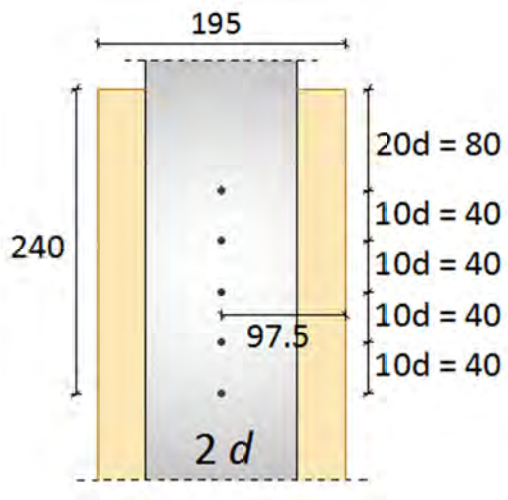


Table 3: Test results from series 2d-2.5-n40.

Specimen	ρ [kg/m³]	F_u [kN]	F_u / nail [kN]	Failure mode
1	443	13,9	2,78	2
2	443	13,1	2,62	2
3	443	13,8	2,76	2
4	520	12,5	2,5	2
5	520	7,1	1,42	-
6	520	13,6	2,72	2
Mean	482	**13,4**	**2,68**	
Charact.	414	**12,5**	**2,49**	

Mean and characteristic values shown in table 3 do not include the specimen that failed in brittle manner. Specimen number 5 had a big crack in the line of the nails and it's believed that this triggered the splitting failure.

2d-5-n40

Six specimens were tested with this setup. Five of them failed in ductile manner and one failed in brittle (splitting). For the ductile failures the observed failure mode was 2, mode d) fig. 3. The results from the tests are given in table 4.

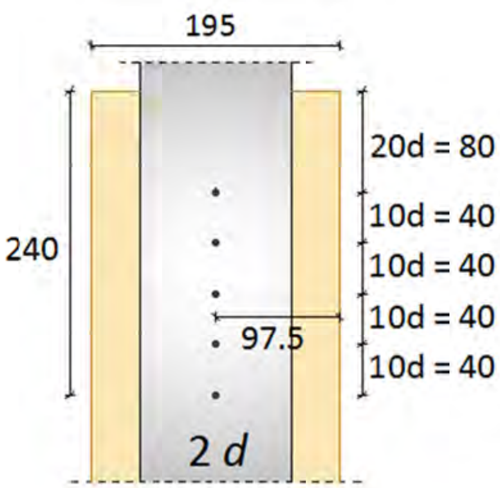


Table 4: Test results from series 2d-5-n40.

Specimen	ρ [kg/m^3]	F_u [kN]	F_u / nail [kN]	Failure mode
1	440	10,4	2,08	2
2	429	11,8	2,36	2
3	440	8,7	1,74	-
4	429	12,2	2,44	2
5	440	9,6	1,92	2
6	429	12,9	2,58	2
Mean	435	**11,4**	**2,28**	
Charact.	425	**9,8**	**1,96**	

Mean values and characteristic values shown in table 4 do not include the specimen that failed in brittle manner. Specimen number 3 showed no obvious defects before testing.

Series 4d

4d-2.5-n40

Six specimens were tested with this setup. All of them failed in ductile manner. The observed failure mode was 2, mode d) fig. 3. This pattern resembles series 2d-2.5-n40 but it has nail spacing a1=80mm instead of 40. The results from the tests are given in table 5.

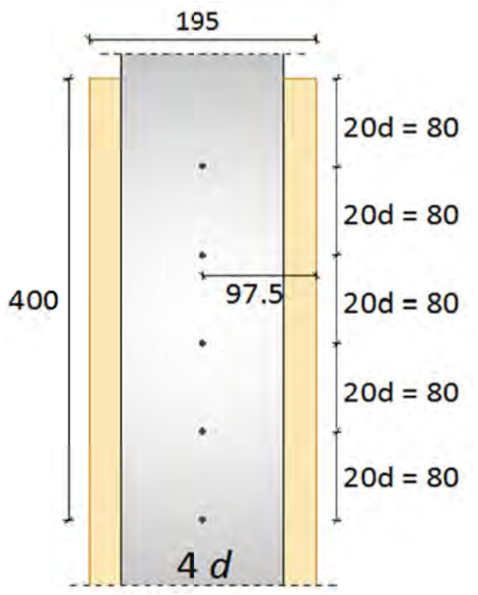


Table 5: Test results from series 4d-2.5-n40.

Specimen	ρ [kg/m^3]	F_u [kN]	F_u / nail [kN]	Failure mode
1	463	14	2,8	2
2	446	11,9	2,38	2
3	444	10,8	2,16	2
4	443	11,2	2,24	2
5	449	12,3	2,46	2
6	506	10,9	2,18	2
Mean	459	**11,9**	**2,37**	
Charact.	420	**9,9**	**1,99**	

4d-5-n40

Six specimens were tested with this setup. All of them failed in ductile manner. The observed failure was 2, mode d) fig. 3. This pattern resembles series 2d-5-n40 but it has nail spacing a1=80mm instead of 40. The results from the tests are given in table 6.

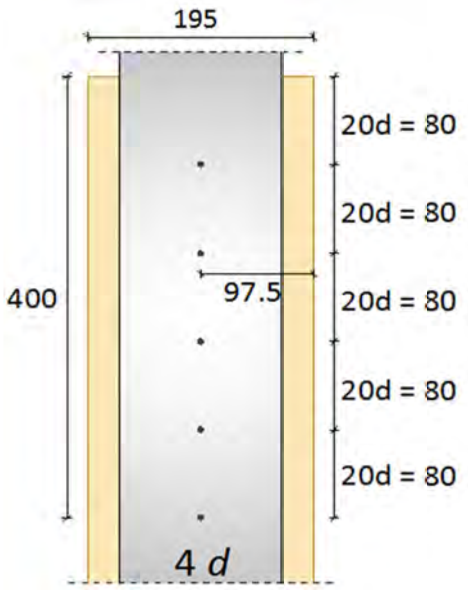


Table 6: Test results from series 4d-5-n40.

Specimen	**ρ [kg/m³]**	**F_u [kN]**	**F_u / nail [kN]**	**Failure mode**
1	454	11,7	2,34	2
2	435	12,8	2,56	2
3	435	12,2	2,44	2
4	435	10,7	2,14	2
5	506	11,6	2,32	2
6	506	11,2	2,24	2
Mean	462	**11,7**	**2,34**	
Charact.	406	**10,5**	**2,1**	

4d-2.5-n60

Six specimens were tested with this setup. All of them failed in ductile manner. The observed failure mode was 3, mode e) fig. 3. The results from the tests are given in table 7.

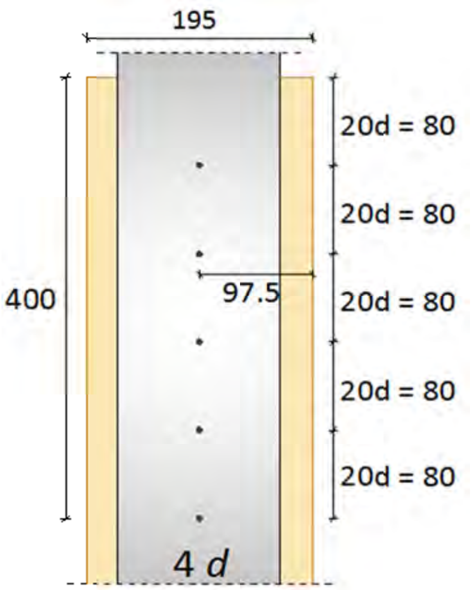


Table 7: Test results from series 4d-2.5-n60.

Specimen	ρ [kg/m^3]	F_u [kN]	F_u / nail [kN]	Failure mode
1	451	16,7	3,34	3
2	454	16,7	3,34	3
3	454	14,8	2,96	3
4	454	15,3	3,06	3
5	444	15,8	3,16	3
6	444	15,1	3,02	3
Mean	450	**15,7**	**3,15**	
Charact.	442	**14,4**	**2,89**	

4d-5-n60

Six specimens were tested with this setup. All of them failed in ductile manner. The observed failure mode was 3, mode e) fig. 3. The results from the tests are given in table 8.

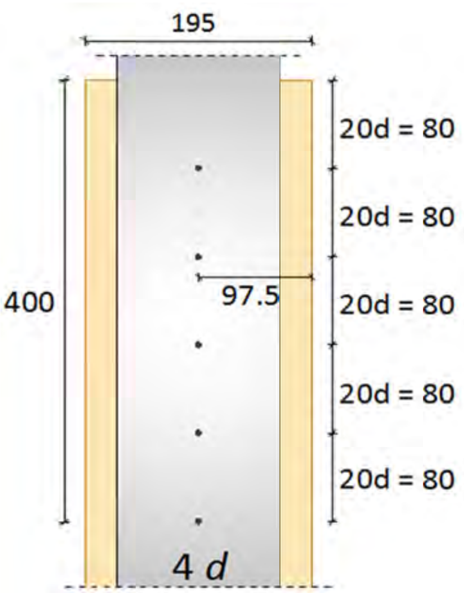


Table 8: Test results from series 4d-5-n60.

Specimen	ρ [kg/m³]	F_u [kN]	F_u / nail [kN]	Failure mode
1	449	15,3	3,06	3
2	488	17,4	3,48	3
3	494	15,2	3,04	3
4	494	15,7	3,14	3
5	488	17,1	3,42	3
6	488	14,7	2,94	3
Mean	484	**15,9**	**3,18**	
Charact.	456	**14,2**	**2,83**	

1d-2.5-n40

Eight specimens were tested with this series. All of them failed in ductile manner. The observed failure mode was 2 and 3, mode d) and e) fig. 3. The results from the tests are given in table 9.

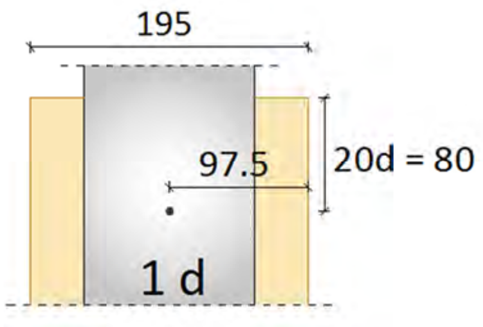


Table 9: Test results from series 1d-2.5-n40.

Specimen	ρ [kg/m^3]	F_u [kN]	Failure mode
1	439	3,01	3
2	450	2,75	2
3	439	2,56	2-3
4	474	3,35	3
5	450	2,85	2-3
6	439	2,9	2
7	474	3,35	2
8	450	3,05	3
Mean	452	**2,98**	
Charact.	428	**2,53**	

1d-5-n40

Nine specimens were tested with this series. All of them failed in ductile manner. The observed failure mode was 2 and 3, mode d) and e) fig. 3. The results from the tests are given in table 10.

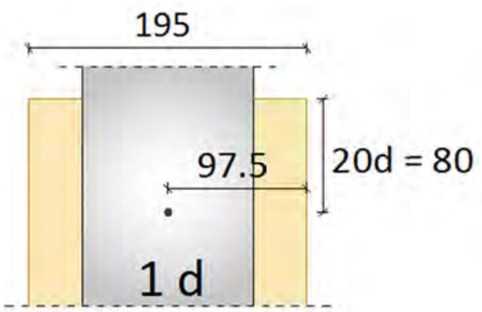


Table 10: Test results from series 1d-5-n40.

Specimen	ρ [kg/m^3]	F_u [kN]	Failure mode
1	399	2,75	2
2	449	3,2	2
3	418	3,32	3
4	399	2,81	2-3
5	449	3	2-3
6	418	2,96	2
7	399	2,9	2
8	449	2,76	2
9	418	3,35	2
Mean	422	**3,01**	
Charact.	386	**2,62**	

4.2.1 Analysis – Ductile failure

In this section analysis of the test results is carried out. The results will be compared with the data from the simulation model which used the Johansen's yield theory and with standard design approach from Eurocode 5. Eurocode 5 will use characteristic values. Characteristic density for C30 is 380 kg/m^3 and characteristic yield moment is 6616 Nmm^2, using 600N/mm^2 as tensile strength. In the tables below the columns with resistance according to Johansen's yield theory will use density and plastic moment capacity as explained in chapter 4.1, see also appendix D.

Analysis 2d-2.5-n40

In the nails that presented one plastic hinge, the hinge was formed at the interface between the steel plate and the timber. This is expected when using a thick steel plate (failure mode 2, d) see fig 3.) because it acts as a fixed support. When using a thin steel plate (failure mode 2 b), see fig 3.) the plate acts as a pinned support allowing the nail to rotate in the hole and the plastic hinge is formed further inside the timber. The plate used in this series is considered to be in between thick and thin but closer to thin, still it behaves as a thick plate in regard to both hinge formation and failure load.

The specimen that failed due to splitting had almost straight nails at a failure load of 7.1 kN. This specimen had a big crack in the line were the nails were going to be placed which most likely influenced the splitting failure.

The results from the tests and simulations are shown in table 11.

Table 11: Test and simulation results 2d-2.5-n40.

Source 2d-2.5-n40	Test Result [kN]	Johansen's Interpol [kN]	Johansen's Thick plate [kN]	EC 5 [kN]
Mean	2,68	1,42	1,75	-
Charact.	2,49	1,18	1,48	1.15

As seen in table 11 both mean and characteristic values are about twice the size of the interpolated values obtained from the simulation model. The plate used acted as a thick plate according to the definition in Eurocode and the values given from the thick plate formulation are better suited with the test results, see table 11 Johansen's Thick plate column.
This together with the placement of the plastic hinge could be an indicator that even the 2.5mm plate can act as a fixed support contrary to what the code suggests.

Eurocode 5 characteristic value is around 50% of the characteristic value from the tests, and this is before safety factors are introduced and reduction for multiple nails in a row is taken into account.

Analysis 2d-5-n40

One plastic hinge was observed on almost all nails. The plastic hinge was formed at the interface between the steel plate and the timber. Since two plates were used with the combined thickness of 5mm, the location where the plastic hinge was formed was expected and according to the theory.

The results from the test and simulations are shown in table 12.

Table 12: Test and simulation results 2d-5-n40.

Source 2d-5-n40	Test Result [kN]	Johansen's Thick plate [kN]	EC 5 [kN]
Mean	2,28	1,67	-
Charact.	1,96	1,41	1,4

As seen in table 12 both mean and characteristic values from the tests are close to the simulated values. The Eurocode characteristic value is also close because the formulation for failure mode 2 is basically the same for both Johansen's yield theory and Eurocode.

2d-2.5-n40 versus 2d-5-n40

Comparing the test results from 2d-5-n40 with the 2d-2.5-n40 series, the mean value per nail is lower for the thick plate setup by almost 0,5kN, see table 13. The fact that the 2d-5 series had lower mean density could be one reason. Another reason could be that the 2d-5 series had a lower penetration depth due to the use of a thicker plate. Lower penetration length will result in lower resistance values.

Table 13: 2d-2.5-n40 versus 2d-5-n40.

Source	Test Result [kN]	ρ [kg/m^3]
2d-2.5-n40	2,68	482
2d-5-n40	2,28	435

Analysis 4d-2.5-n40

One plastic hinge was observed at the steel timber interface, as in the case with the 2d-2.5-n40 series. As in the case with the 2d pattern the mean resistance per nail was significantly higher than the interpolation resistance given from the simulation. The Johansen's thick resistance value is closer to the test results, see table 14. The plate acts more like a thick plate than a thin even though it's closer to the thin plate range.

Table 14: Test and simulation results 4d-2.5-n40.

Source (4d-2.5-n40)	Test Result [kN]	Johansen's Interpol [kN]	Johansen's Thick [kN]	EC 5 [kN]
Mean	2,37	1,42	1,75	-
Charact.	1,99	1,18	1,48	1,15

Analysis 4d-5-n40

One plastic hinge was formed at the steel timber interface. Table 15 shows the test and simulation results from 4d-5-n40. Like with the previous 5mm plate setups the Johansen's thick simulation values are close to the real test values.

Table 15: Test results and simulation results for 4d-5-n40.

Source (4d-5-n40)	Test Result [kN]	Johansen's Thick [kN]	EC 5 [kN]
Mean	2,34	1,67	-
Charact.	2,1	1,41	1,4

4d-2.5-n40 versus 4d-5-n40

Mean and characteristic values for the different patterns are almost the same, see table 16. A reason could be that the mean densities for both series are close to each other.

Table 16: 4d-2.5-n40 versus 4d-5-n40.

Source	Test Result [kN]	ρ [kg/m^3]
4d-2.5-n40	2,37	459
4d-5-n40	2,34	462

Analysis 4d-2.5-n60

Two plastic hinges were observed on the nails. Even with the 60mm nails the plate acts as a thick plate bending the nail at two points. The result from the simulation also suggests that Johansen's thick plate formulation is more realistic than the values obtained from interpolating between the thin and thick plate formulations.

Table 17: Test results and simulation results for 4d-2.5-n60.

Source (4d-2.5-n60)	Test Result [kN]	Johansen's Interpol [kN]	Johansen's Thick [kN]	EC 5 [kN]
Mean	3,15	1,46	1,88	-
Charact.	2,89	1,3	1,67	1,15

Analysis 4d-5-n60

Two plastic hinges were formed on the nails in this series. Like with the previous 5mm plate setups the Johansen's thick values from the simulations are close to the real test values.

Table 18: Test results and simulation results for 4d-5-n60.

Source (4d-5-n60)	Test Result [kN]	Johansen's Thick [kN]	EC 5 [kN]
Mean	3,18	1,88	-
Charact.	2,83	1,67	1,47

4d-2.5-n60 versus 4d-5-n60

The mean and characteristic values for the different patterns are almost the same, see table 19. A reason could be that the mean densities for both series are close to each other.

Table 19: 4d-2.5-n60 versus 4d-5-n60.

Source	Test Result [kN]	ρ [kg/m^3]
4d-2.5-n60	3,15	450
4d-5-n60	3,18	484

Analysis 1d-2.5-n40

One plastic hinge was formed at the steel timber interface, but some nails presented two. The forming of two plastic hinges should not occur according to the simulations that were run. An explanation for this could be that there are a lot of knots in some of the specimens. These knots can run perpendicular to a nail, preventing it from bending in a straight line acting as a support, thus bending it at another point besides the one at the interface between the plate and the timber. The test results are higher than the interpolation resistance given from the simulations, the plate acts once again like a thick plate.

Table 20: Test results and simulation results for 1d-2.5-n40.

Source (1d-2.5-n40)	Test Result [kN]	Johansen's Interpol [kN]	Johansen's Thick [kN]	EC 5 [kN]
Mean	2,98	1,42	1,75	-
Charact.	2,53	1,18	1,48	1,15

Analysis 1d-5-n40

One plastic hinge was formed at the steel timber interface, but some nails presented two.

Table 21: Test results and simulation results for 1d-5-n40.

Source (1d-5-n40)	Test Result [kN]	Johansen's Thick [kN]	EC 5 [kN]
Mean	3,01	1,67	-
Charact.	2,62	1,41	1,4

1d-2.5-n40 versus 1d-5-n40

Mean and characteristic values for the different patterns are almost the same, see table 22. A reason could be that the mean densities for both series are close to each other.

Table 22: 1d-2.5-n40 versus 1d-5-n40.

Source	Test Result [kN]	ρ [kg/m^3]
1d-2.5-n40	2,98	452
1d-5-n40	3,01	422

Conclusion ductile results

After analyzing the ductile results the following conclusions were made:

- Two plastic hinges could form in the series that used 40mm nails even though Eurocode suggests it cannot occur. An explanation for this could be knots in the timber that act as a support under the nail bending it at an additional point besides the point at the steel and timber interface.

- One plate with thickness of 2.5mm seems to give same results, in some cases even better, than the same nail pattern with two plates with 5mm thickness. The resistance according to Eurocode when using a 2.5mm plate should be interpolated between the thick and thin formulations, and because the 2.5mm plate is closer to the thin plate border at 2mm it gives substantially lower resistance values than the test results. This was valid when both 40mm and 60mm nails were used.

- In the series that used 2.5mm plates, a plastic hinge was formed at the interface between the timber and the steel plate. This means that the plate acted as a fixed support even though the 2.5mm plate was closer to the thin plate border at 2mm. This was valid when both 40mm and 60mm nails were used.

- Nail spacing parallel to the grain does not seem to influence the resistance of the joint even though it should be reduced because of the risk for premature splitting. For example the 2d-2.5-n40 series had the highest mean value of the multiple nail connections with 40mm nails, see table 23. Series 2d had nail spacing parallel to the grain equal to 10d. Both series had one specimen that failed with splitting failure. If one designs a pattern like the 2d series according to Eurocode the resistance will be the following.

  $f_d = k_{mod} * \frac{f_k}{\gamma_m}$
  $f_k = n_{eff} * R_{ec5}$
  $n_{eff} = n^{k_{eff}}$

  where:
  γ_m is the partial factor for a material property
  k_{mod} is a modification factor taking moisture and load duration into account
  f_d is the design resistance of the joint according to Eurocode
  f_k is the characteristic resistance of the joint according to Eurocode
  n_{eff} is the effective number of nails in a row
  R_{ec5} is the resistance according to Eurocode

  Nail spacing parallel to grain, a1=10d. Table 1 gives k_{eff}=0,85
  k_{mod} = 0,9 (Climate class 1, Short load duration) [7]
  $n_{eff} = 5^{0,85} = 3,9$

  For 2d-2,5-n40:
  $R_{ec5} = 1,15\ kN$
  $f_k = 3,9 * 1,15 = 4,49kN$

$$f_d = 0{,}9 * \frac{4{,}49}{1{,}25} = 3{,}23\ kN$$

Load per nail: 3,23/5= 0,64 kN

For 2d-5-n40:

$$R_{ec5} = 1{,}4\ kN$$
$$f_k = 3{,}9 * 1{,}4 = 5{,}46 kN$$
$$f_d = 0{,}9 * \frac{5{,}46}{1{,}25} = 3{,}93\ kN$$

Load per nail: 3,93/5= 0,79 kN

For the brittle specimen in the 2d-2,5-n40 series the failure load per nail was 1,42kN, this is around 120% more than the design value given by Eurocode.
For the brittle specimen in the 2d-5-n40 series the failure load per nail was 1,74kN, this is around 120% more than the design value given by Eurocode.

As mentioned before only two specimens showed brittle behavior while the remaining ten failed in ductile manner. Though splitting occurred as predicted by Eurocodes nail spacing criteria the design value obtained was significantly lower than the failure load in the brittle specimens.

- The 40mm 1d series showed the highest resistance per nail when compared to the other 40mm nails series.

Table 23: All ductile test results.

Source	Test Result (Mean) [kN]	ρ [kg/m^3]
1d-2.5-n40	2,98	452
1d-5-n40	3,01	422
4d-2.5-n40	2,37	459
4d-5-n40	2,34	462
2d-2.5-n40	2,68	482
2d-5-n40	2,28	435
4d-2.5-n60	3,15	450
4d-5-n60	3,18	484

Figure 15: Typical nail appearance for the 2d-2.5-n40 series.

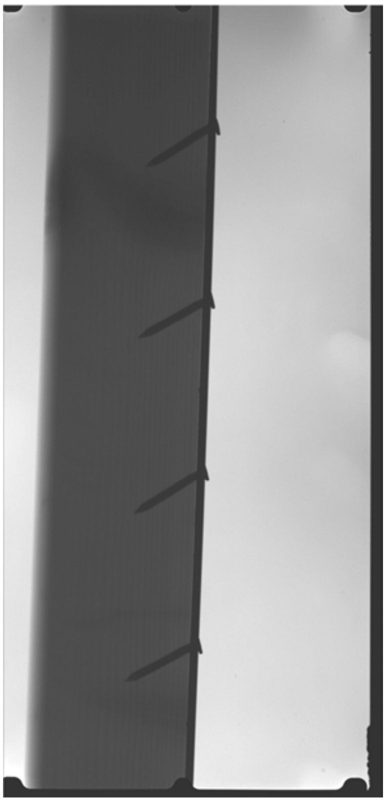


Figure 16: X-ray picture at maximum load on the 4d-2.5.n40 series, one plastic hinge formed at the steel timber interface.

Figure 17: X-ray image at high load, 4d-2.5-n60, two plastic hinges visible.

4.3 Results - Plug shear failure

Six different plug shear patterns were designed. The aim of the different patterns was to understand more about plug shear failure in these types of joints. A number of parameters such as nail length, density of nails, nailed joint width and length etc. were varied in order to find a connection between the nail patterns used and the failure load.

The nail length will vary the tension and side shear areas of the plug, for example a longer nail length will penetrate further into the timber allowing more area to be active at both the tension face and the side faces. Denser nail placement will allow the plug to form before the nails reach their full capacity. Different nailed joint width and length will also increase and decrease the tension, bottom and side faces. When presenting the results from the test information about the plug that formed will also be included. The tables will have abbreviations which are explained below.

PL- Measured plug length
PW – Measured plug width
p – Timber density
A/n – Surface Area per nail
SA – Side shear area
BA – Bottom shear area
TA – Tension area
PD – Plug depth
F_u – Failure load
F_u/n – Failure load per nail

While performing the plug shear tests a certain failure pattern was observed. This scenario will be presented below.

- Load increase until a middle crack opened up in the timber. It ran through the entire bottom part of the timber. This crack did not affect the load. Small cracking sounds were audible.

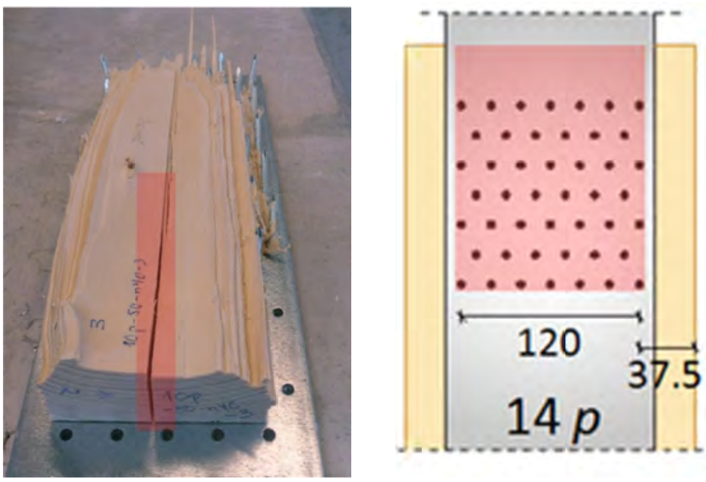
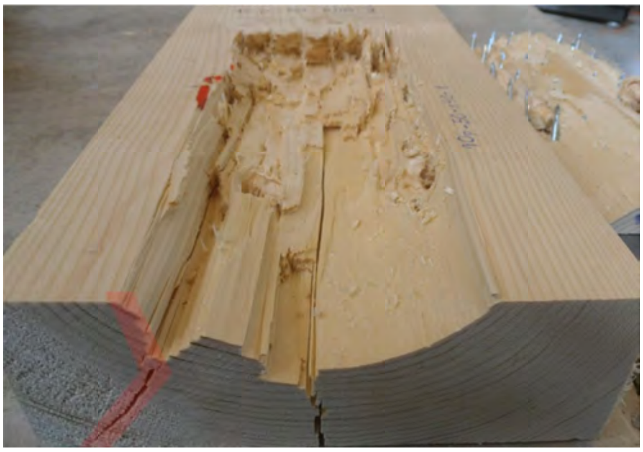
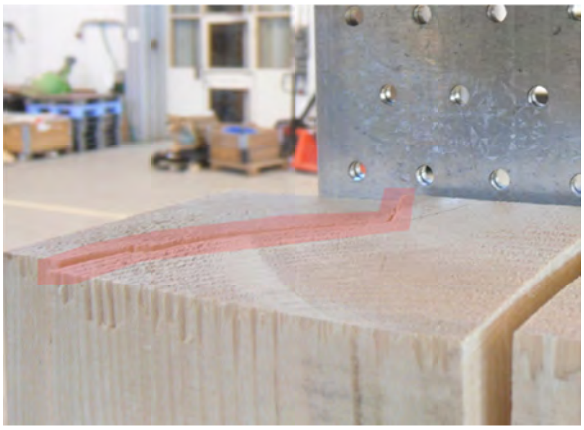


Figure 18: Left image: Middle crack visible in the red area.
Right image: Definition of surface area per nail.

- Small cracking sounds in the timber were audible after first crack. The load continued to increase.



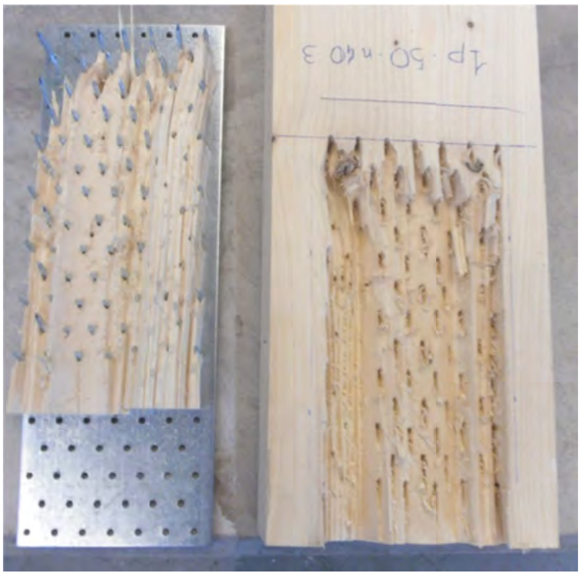


- Three outcomes were possible at this stage:

  - One of the two sides would crack open. It was difficult to tell how far the crack developed into the timber. Afterwards the second side would fail with or without the rest of the plug. It was very difficult to visually confirm this.

  - The tension side would fail cracking open the sides, leaving the bottom of the plug still attached. The plug would hang out with the bottom at a small angle, see fig. below.

  - The entire plug would fail seemingly at the same time, ending the plug shear test abruptly. The nails would still grip the timber element allowing for some resistance. This was only possible due to the low loading speed of 1mm/min.



1p-5-n40

Six specimens were tested with this setup. All failed with plug shear failure. Specimen nr 1 was nailed with a nail gun. The pressure of the nail gun was high and it is believed that this caused cracks in the timber. Because of this, the failure load for this specimen is suspiciously low and will be excluded from the analysis. All specimens had a Failure load/nail range that is typical for plug shear failure 1.1-1.7kN/nail. Fig. 21 shows an X-ray image of one specimen after it failed with plug shear. The plug shear line is clearly visible as the white line in fig 21.

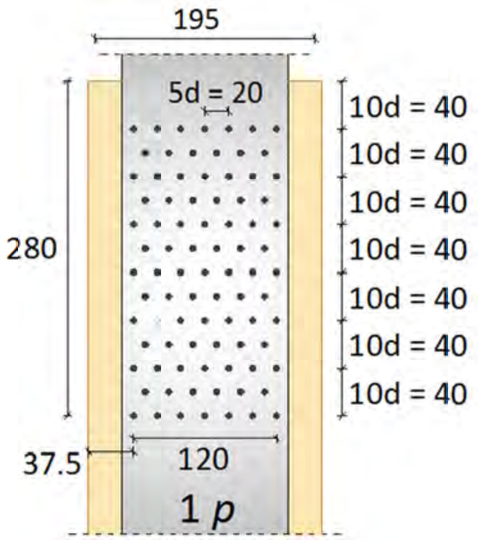


Table 24: Test results and joint information from series 1p-5-n40.

Spec.	PL [m]	PW [m]	*p* [kg/m³]	A/n [mm²/nail]	SA [mm²]	BA [mm²]	TA [mm²]	PD [mm]	F_u [kN]	F_u/n [kN/nail]
1	270	120	377	381	14524	31332	3212	27	100,6	1,2
2	260	120	383	381	8784	30132	2012	17	112,8	1,3
3	265	120	428	381	12134	30732	2732	23	103,8	1,2
4	270	120	495	381	16684	31332	3692	31	146,9	1,7
5	270	100	364	381	10744	25932	1972	20	92,0	1,1
Mean	**267**	**116**	**409**	**381**	**12574**	**29892**	**2724**	**24**	**111,2**	**1,3**

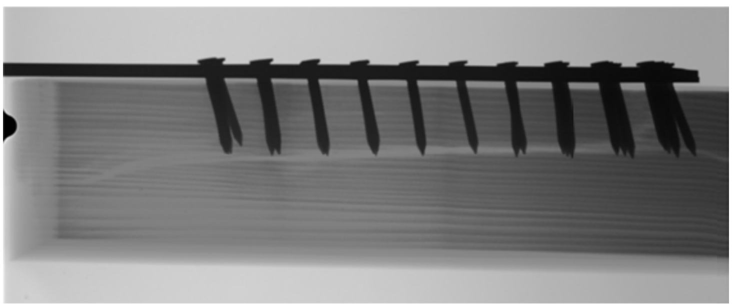


Figure 21: Plug shear line visible as the white line in the X-ray image.

10p-5-n40

Five specimens were tested with this setup. All failed with plug shear failure. Two of them failed with a higher load, 2.2 and 2.3 kN/nail which is often considered to be in the ductile range. For these specimens one plastic hinge was observed after removing the nails, see fig. 22.

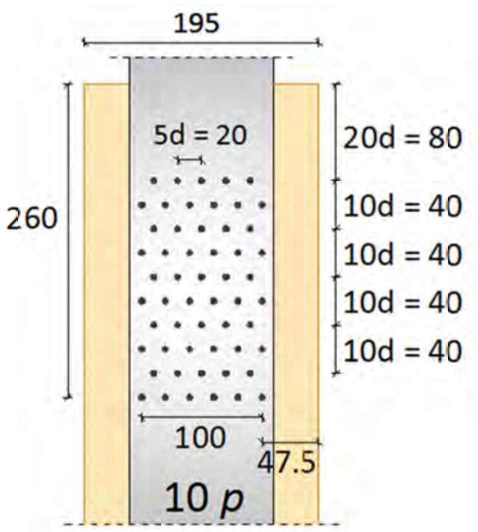


Table 25: Test results and joint information from series 10p-5-n40.

Spec.	PL [m]	PW [m]	*p* [kg/m^3]	A/n [mm^2/nail]	SA [mm^2]	BA [mm^2]	TA [mm^2]	PD [mm]	F_u [kN]	F_u/n [kN/nail]
1	255	100	362	454	12710	24809	2476	25	79,0	1,4
2	250	90	472	454	16460	21809	2946	33	121,5	2,2
3	250	100	475	454	18460	24309	3676	37	124,3	2,3
4	250	100	360	454	14960	24309	2976	30	78,0	1,4
5	250	100	413	454	13460	24309	2676	27	90,2	1,6
Mean	**251**	**98**	**416**	**454**	**15210**	**23909**	**2950**	**30**	**98,6**	**1,8**

d.

10p-5-n60

Five specimens were tested with this setup. This pattern is similar to 10p-5-n40 but uses 60mm nails instead of 40mm. Two of them failed with a higher load, 2.1 and 2.5 kN/nail which is often considered to be in the ductile range. For these specimens one plastic hinge was observed after removing the nails.

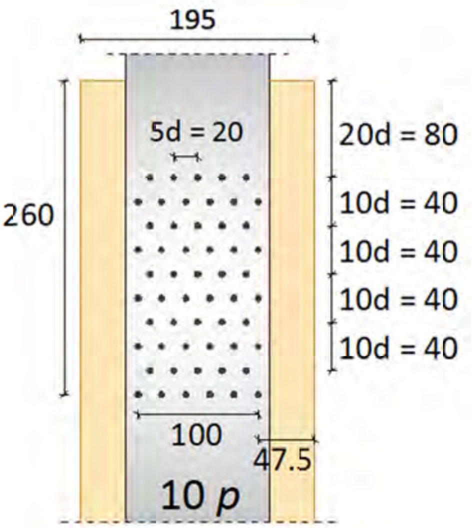
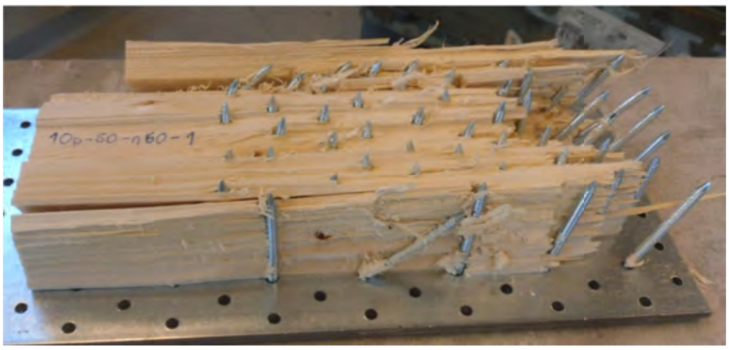


Table 26: Test results and joint information from series 10p-5-n60.

Spec.	PL [m]	PW [m]	*p* [kg/m^3]	A/n [mm^2/nail]	SA [mm^2]	BA [mm^2]	TA [mm^2]	PD [mm]	F_u [kN]	F_u/n [kN/nail]
1	250	100	421	454	15460	24309	3076	31	73,5	1,3
2	250	100	424	454	16460	24309	3276	33	113,7	2,1
3	230	120	481	454	16520	26909	4296	36	102,1	1,9
4	250	80	441	454	16460	19309	2616	33	135,1	2,5
5	250	90	468	454	19960	21809	3576	40	89,5	1,6
Mean	**246**	**98**	**447**	**454**	**16972**	**23329**	**3368**	**35**	**102,8**	**1,9**



13p-5-n40

Six specimens were tested with this setup. All failed with plug shear failure. The load per nail was high in this series averaging 1.9 kN/nail.

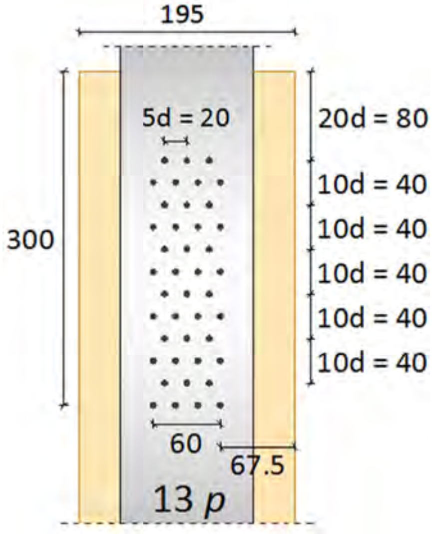


Table 27: Test results and joint information from series 13p-5-n40.

Spec.	PL [m]	PW [m]	*p* [kg/m³]	A/n [mm²/nail]	SA [mm²]	BA [mm²]	TA [mm²]	PD [mm]	F_u [kN]	F_u/n [kN/nail]
1	280	60	400	414	11152	16272	1184	20	84,0	2,0
2	290	60	441	414	9812	16872	1004	17	80,0	1,9
3	290	60	395	414	11552	16872	1184	20	72,0	1,7
4	290	60	429	414	11552	16872	1184	20	96,2	2,3
5	290	60	430	414	12132	16872	1244	21	83,0	2,0
6	280	60	412	414	13952	16272	1484	25	72,0	1,7
Mean	**287**	**60**	**418**	**414**	**11692**	**16672**	**1214**	**21**	**81,2**	**1,9**

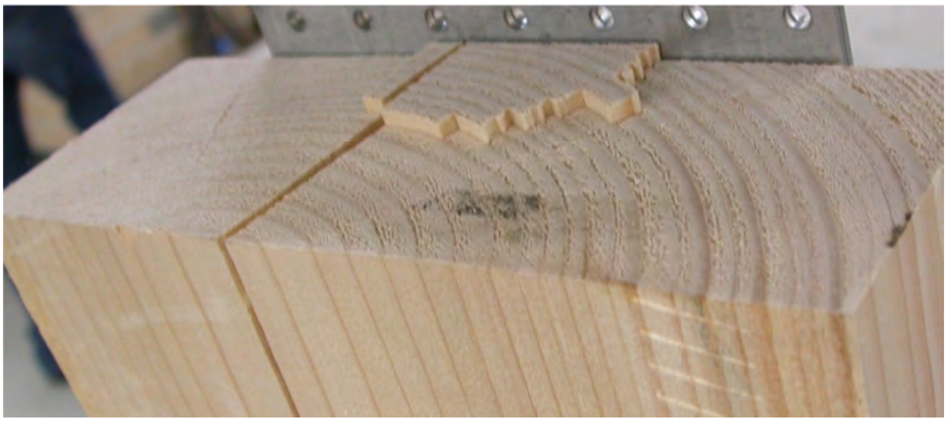


Figure 24: Plug formed in one of the specimens tested.

14p-5-n40

Six specimens were tested with this setup. All failed with plug shear failure except for one specimen which failed in ductile manner. All specimens had high load per nail in the range 2.0-2.3kN/nail. The mean value row in table 28 does not include the ductile specimen nr 6.

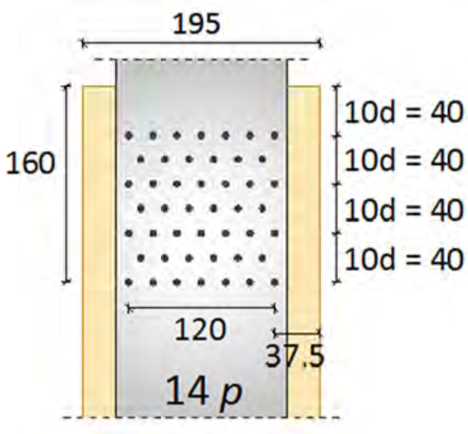


Table 28: Test results and joint information from series 14p-5-n40.

Spec.	PL [m]	PW [m]	*p* [kg/m³]	A/n [mm²/nail]	SA [mm²]	BA [mm²]	TA [mm²]	PD [mm]	F_u [kN]	F_u/n [kN/nail]
1	150	120	447	417	8068	17422	3212	27	95,0	2,1
2	155	120	445	417	6788	18022	2612	22	92,0	2,0
3	150	120	423	417	5068	17422	2012	17	100,0	2,2
4	160	120	480	417	7968	18622	2972	25	108,0	2,3
5	160	120	489	417	7328	18622	2732	23	107,0	2,3
6	160	120	496	417	-	-	-	-	119,9	2,6
Mean	**155**	**120**	**457**	**417**	**7044**	**18022**	**2708**	**23**	**100,4**	**2,2**

Figure 25: Disassembled specimen showing the plug and the hole left in the timber.

15p-5-n40

Six specimens were tested with this setup. All failed with plug shear failure. The load per nail was high in this series averaging 1,9 kN/nail.

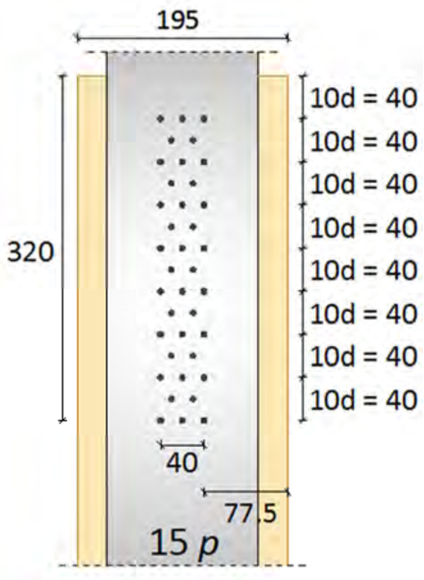


Table 29: Test results and joint information from series 15p-5-n40.

Spec.	PL [m]	PW [m]	*p* [kg/m³]	A/n [mm²/nail]	SA [mm²]	BA [mm²]	TA [mm²]	PD [mm]	F_u [kN]	F_u/n [kN/nail]
1	310	40	476	326	15436	11923	988	25	69,0	1,8
2	310	40	482	326	13576	11923	868	22	60,0	1,6
3	310	40	464	326	14816	11923	948	24	81,0	2,1
4	305	40	456	326	10916	11723	708	18	77,0	2,0
5	320	40	468	326	12736	12323	788	20	70,0	1,8
6	320	40	462	326	15296	12323	948	24	72,0	1,9
Mean	**313**	**40**	**468**	**326**	**13796**	**12023**	**875**	**22**	**71,5**	**1,9**

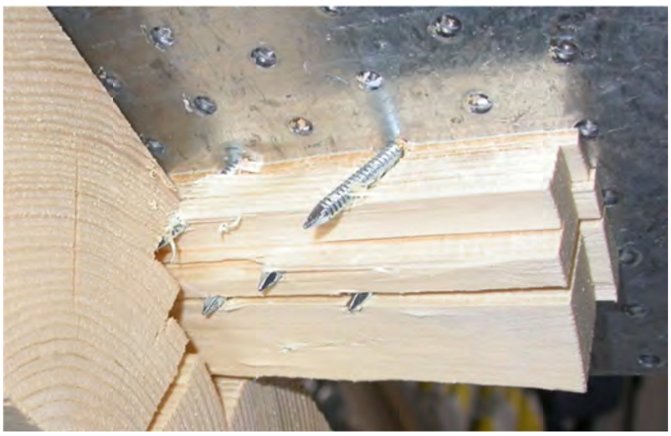


Figure 26: Plug formed in series 15p.

4.3.1 Border pattern results

In order to get more understanding when a joint goes from being ductile to brittle, three different patterns were designed. These nail patterns were designed so that both ductile and brittle failure would occur.

1py-5-n40

Six specimens were tested with this setup. In two of them plug shear failure occurred, the remaining four failed in ductile manner.

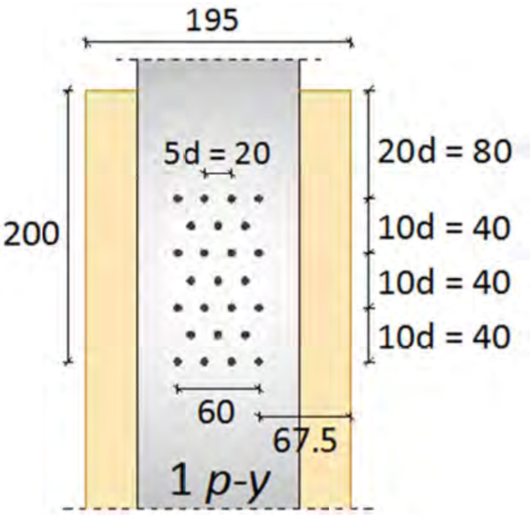


Table 30: Test results from series 1py-5-n40.

Spec.	*p* [kg/m^3]	A/n [mm^2/nail]	FT [D/PS]	F_u [kN]	F_u/n [kN/nail]
1	450	480	D	53,4	2,1
2	424	480	PS	60,7	2,4
3	427	480	PS	56,1	2,2
4	437	480	D	55,2	2,2
5	425	480	D	59,6	2,4
6	418	480	D	55,3	2,2
Mean	**413**	**480**		**56,7**	**2,3**

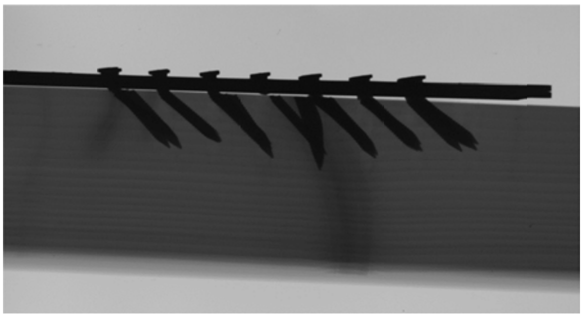


Figure 27: 1py-5-n40, left image: Specimen that failed with ductile failure. Right image: Plug shear failure in a specimen.

3py-5-n40

Four specimens were tested with this setup. In two of them plug shear failure occurred, the remaining two failed in ductile manner.

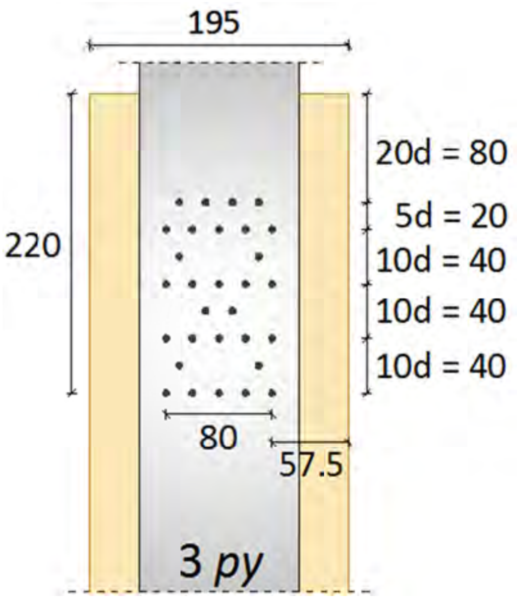


Table 31: Test results from series 3py-5-n40.

Spec.	*p* [kg/m^3]	A/n [mm^2/nail]	FT [D/PS]	F_u [kN]	F_u/n [kN/nail]
1	412	586	PS	61,6	2,1
2	474	586	D	76,8	2,6
3	425	586	PS	61,2	2,0
4	472	586	D	71,7	2,4
Mean	**445**	586		**67,8**	**2,3**

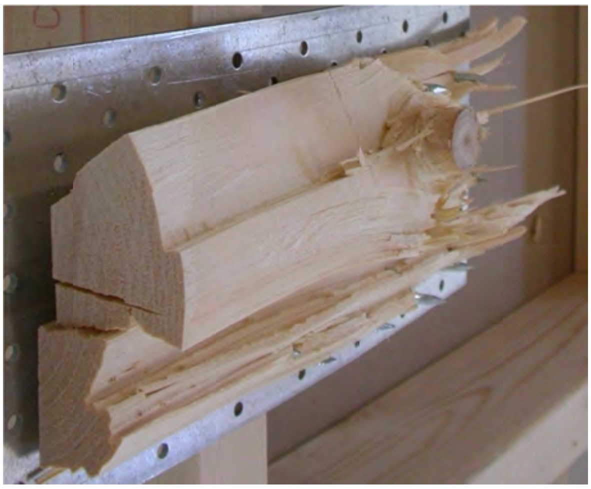


Figure 28: Plug shear failure in one of the specimens, 3py-5-n40 series.

7py-5-n40

Five specimens were tested with this setup. In two of them plug shear failure occurred, the remaining three failed in ductile manner. Fracture line followed the outer most nails.

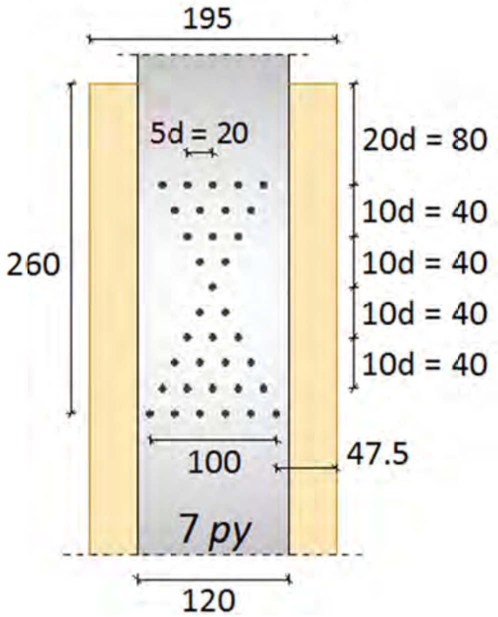
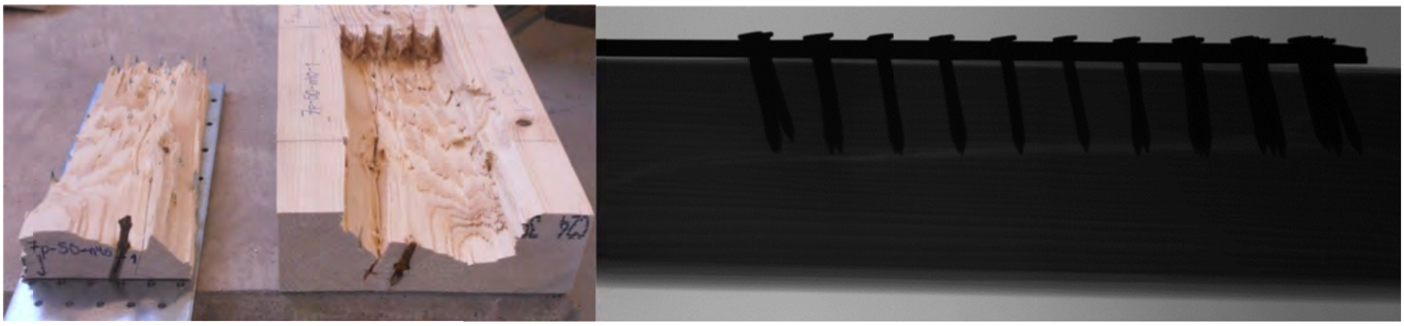


Table 32: Test results from series 7py-5-n40.

Spec.	*p* [kg/m^3]	A/n [mm^2/nail]	FT [D/PS]	F_u [kN]	F_u/n [kN/nail]
1	494	686	PS	85,7	2,45
2	451	686	D	69,6	2,0
3	477	686	D	79,1	2,3
4	528	686	PS	85,4	2,45
5	517	686	D	87,5	2,5
Mean	**493**	**686**		**81,4**	**2,33**



4.3.2 Analysis - Plug shear failure

40mm nails versus 60mm nails
The 10p series were tested with both 40mm and 60mm nails. Even though the penetration depth was 20mm longer for the series with 60mm nails the mean plug depth was only 10mm deeper. The mean failure load was slightly larger for the 10p-5-n60 series, 102.8 versus 98.6 kN for 10p-5-n40.

Influence of density
The density values that were measured for the timber used in the plug shear series should be considered more reliable to use compared to the ductile series. The plug shear series had more area nailed so the actual density of the timber involved in the failure should have a density close to the entire timber elements density value.

Series 1p-5-n40 and 10p-5-n40 were the series that had largest density scatter. These series showed a strong connection between the density and the failure load, see fig 30.

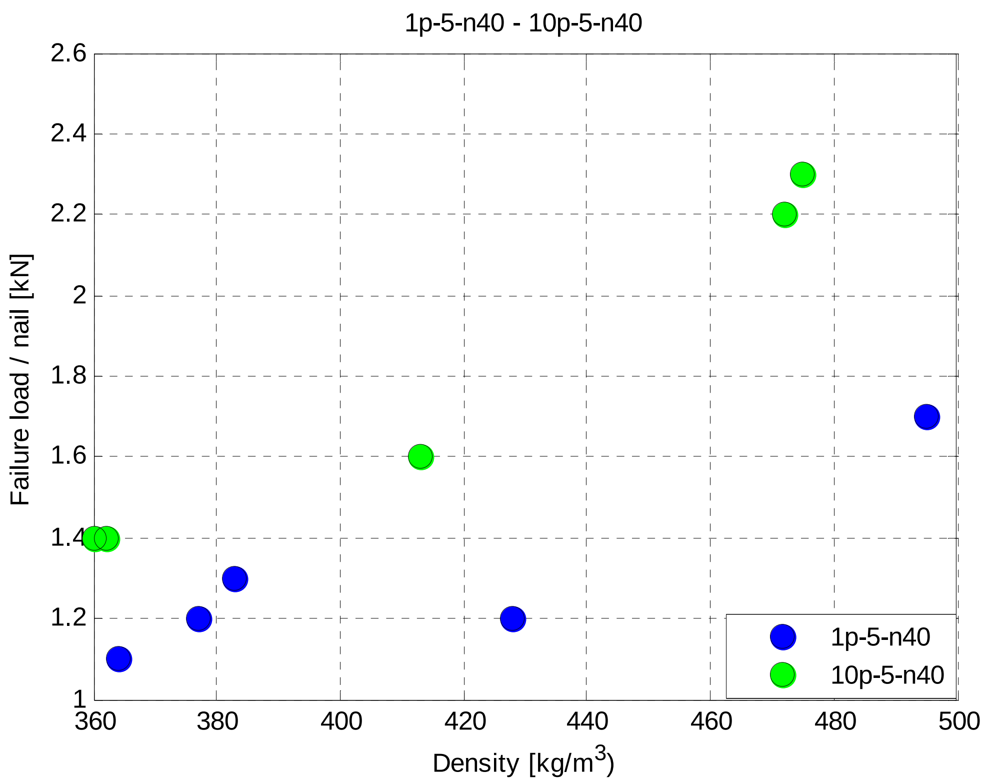


Figure 30: Series 1p-5-n40 blue dot and 10p-5-n40 green dot, Failure load-Density plot.

Both series 10p-5-n60 and 13p-5-n40 had small density scatters if compared to the series in fig.30. Series 13p-5-n40 still shows a trend that with increasing density the failure load will also increase, see fig. 31. This cannot be said for 10p-5-n60. A possible explanation could be that since 60mm nails were used the penetration depth was higher which means there was a higher chance for the plug to come across local variations in the timber, affecting the failure load.

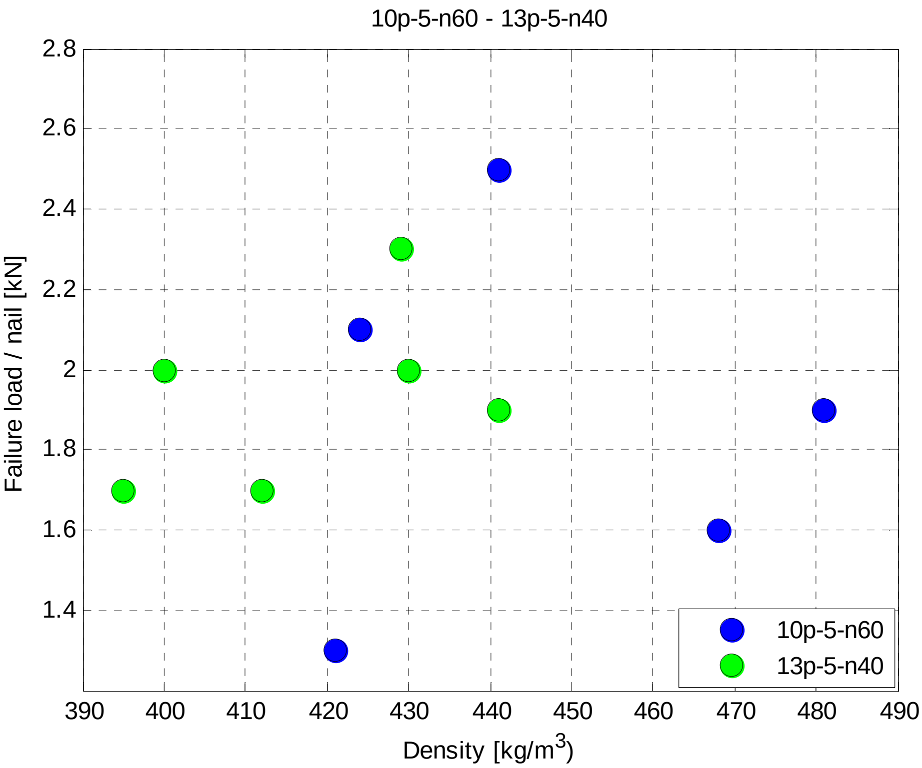


Figure 31: Series 10p-5-n60 blue dot and 13p-5-n40 green dot, Failure load-Density plot.

Of all the plug shear series 15p-5-n40 had the least density scatter, ranging from 456-482 kg/m^3, see fig. 32. The failure loads for the specimens in this series are also concentrated which is a good indicator that the density has influence over the failure load.

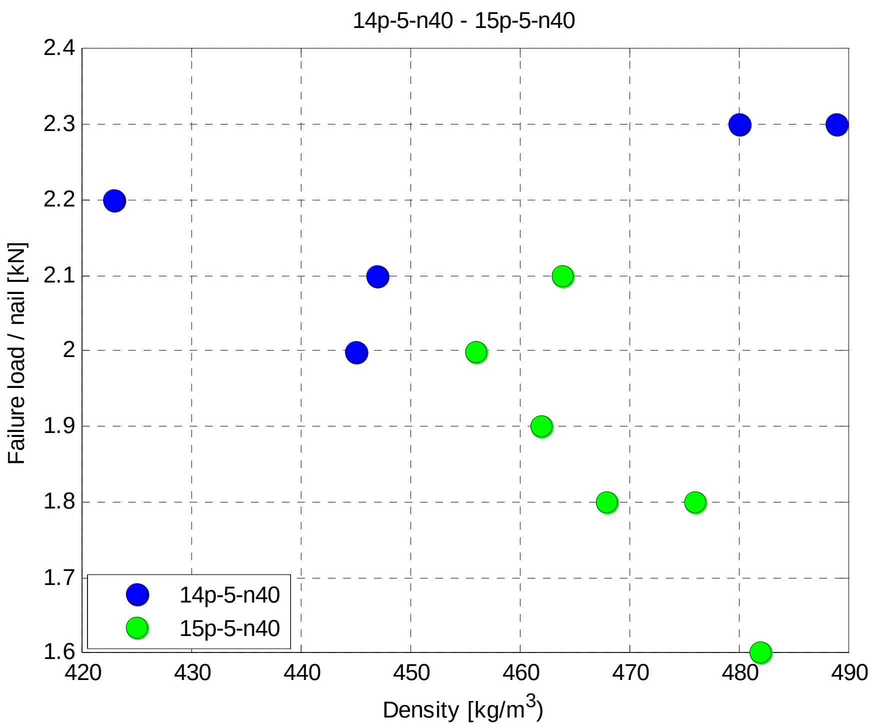


Figure 32: Series 14p-5-n40 blue dot and 15p-5-n40 green dot, Failure load-Density plot.

Evidently the density has some influence on the failure load in plug shear failures. This was expected because there is a relation between the density of the timber and its strength parameters. Taking this information into account the density is a good candidate to include in the formulation that will be decided in the MATLAB model.

Area per nail versus failure load

Area per nail is a measurement of how close the nails are to each other, where a lower value means denser placement. The area is defined as shown in fig. 33. When the density of nails reaches a certain value the joint will fail in plug shear because the resistance for plug shear will be smaller than the ductile resistance. To illustrate this, some ductile data was taken from the d2t series performed by Wrzesniak [6], see table 33. Together with the border and plug shear tests performed in this thesis the graph in fig. 34 was made.

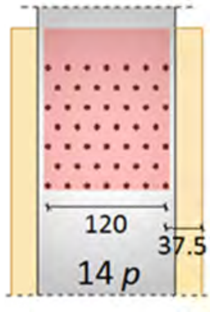


Figure 33: Example of area definition in the expression Area per nail.

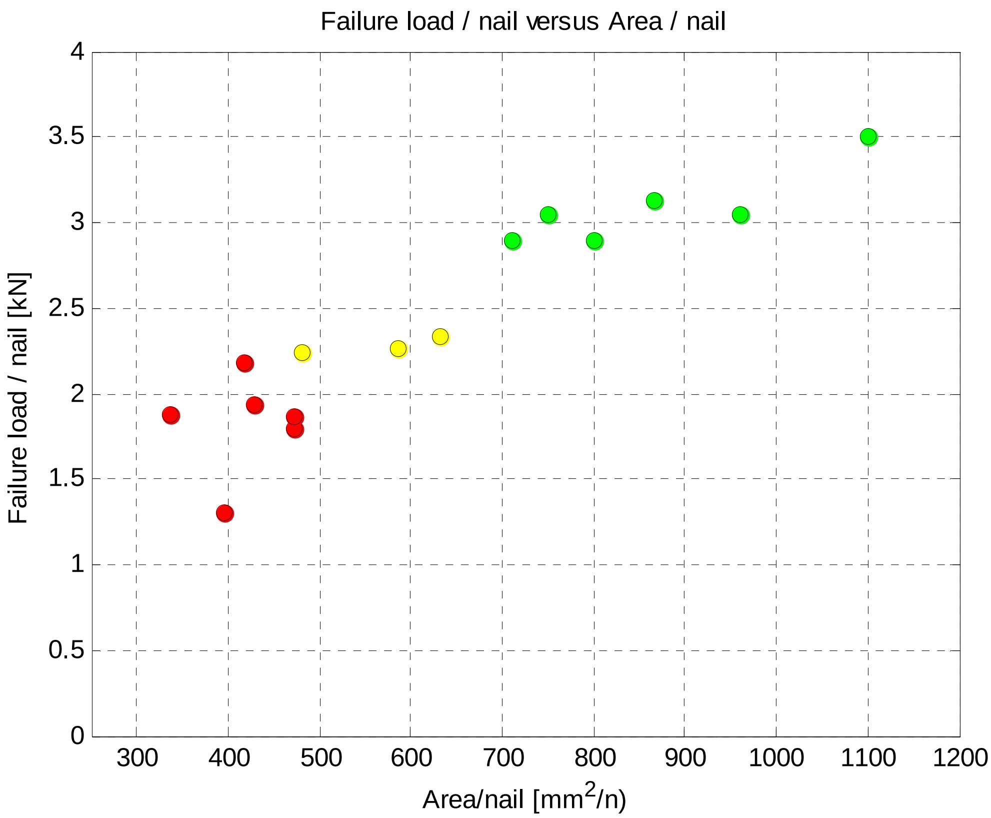


Figure 34: Failure load versus Area/nail plot.

The green dots represent ductile tests, yellow dots border pattern tests and red dots plug shear tests. Fig. 34 shows that as soon the area per nail reaches a certain value, around 600-700 mm^2/nail, a pattern will start to fail in both brittle and ductile manner. If the density of nails is increased even further only plug shear failure occurs.

Table 33: Test results and joint information.

Series	Nails	Area [mm^2]	A/n [mm^2/nail]	F_u [kN]	F_u/nail [kN/nail]	Failure type
1p-5-n40	85	30940	381	111,2	1,31	PS
10p-5-n40	55	24585	454	98,6	1,79	PS
10p-5-n60	55	24035	454	102,8	1,87	PS
13p-5-n40	42	17220	414	81,2	1,93	PS
14p-5-n40	46	18584	417	100,4	2,18	PS
15p-5-n40	38	12502	326	71,5	1,88	PS
1py-5-n40	25	12000	480	56,0	2,24	Border
3py-5-n40	30	17600	586	67,8	2,26	Border
7py-5-n40	35	24000	686	81,4	2,33	Border
d2t14	18	12800	711	52,0	2,89	D
d2t13	16	12000	750	48,8	3,05	D
d2t12	14	11200	800	40,5	2,89	D
d2t5	12	10400	867	37,5	3,13	D
d2t6	10	9600	960	30,5	3,05	D
d2t10	8	8800	1100	28,0	3,5	D

Alternative plug shear formulation based on test results

In order to analyze the plug shear patterns and determine which of the factors influence the failure load, a program in Matlab was written. The program will utilize the function lsqcurvefit to solve nonlinear curve fitting problems in least square sense. The aim was to have a formulation which had variables that were somewhat known before designing a pattern. After reviewing several formulations it was decided to use the following:

$R_{plug,I} = \rho * (\alpha * TA + \beta * SA + \gamma * BA)$ [N]

where:

ρ is the density of the timber [kg/m^3]

α , β and γ are weight factors

TA is the tension area of the plug [mm^2]

SA is the side shear area of the plug in [mm^2]

BA is the bottom shear area of the plug in [mm^2]

The formulation will include several important factors of the timber, such as the density of the timber, which is related to the shear and tension strength. Also, the different areas of the plug are included with constants in front of them. These are the constants that the program will decide when given the information of the failure load, the density of the timber and the different areas of the plug.

Since only six different plug shear patterns were tested it was necessary to include other results from plug shear tests performed by Johansson [3]. Because it’s impossible to know the geometry of the plug without testing the joint, it could be difficult to enter the correct values of the different shear and tension areas in the formulation. For the tests performed in this thesis it was shown that the average plug depth, which will ultimately decide the tension and side areas, was around 2/3 of the penetration depth of the nail. The plug width was in most cases the distance between the far out nails, and the length was the distance from the loaded timber end to the middle of the two top nailed rows, see fig 35.

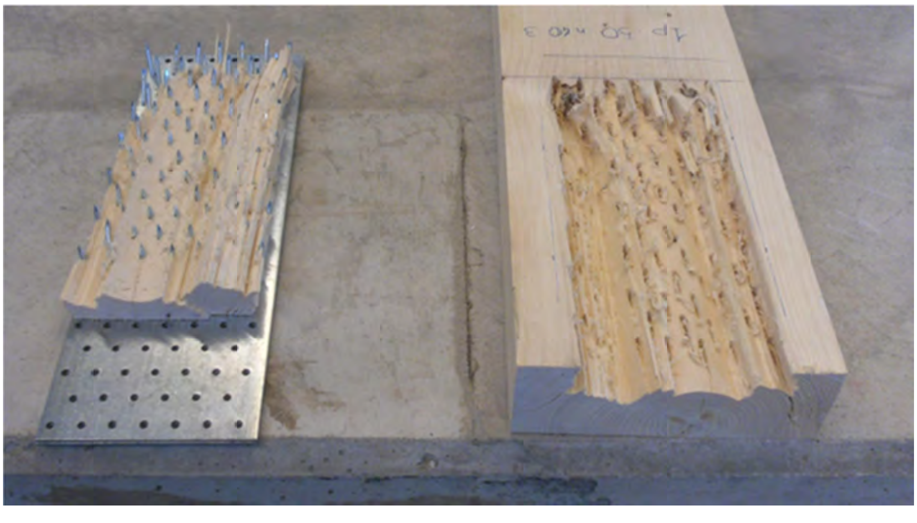


Figure 35: Plug from the 1p-5-n40 series, the plug geometry in this image was typical for the plugs that formed in the series that failed in plug shear.

After running the program the factors α, β and γ were determined to the following values.

$\alpha_I = 1.93 * 10^{-5}$
$\beta_I = 9.16 * 10^{-7}$
$\gamma_I = 8.07 * 10^{-6}$

The final formulation for plug shear failure, valid when the nail density is around 600mm^2/nail and lower, is given by the expression below:

$$R_{plug,I} = \rho * (1{,}93 * 10^{-5} * TA + 9{,}16 * 10^{-7} * SA + 8{,}07 * 10^{-6} * BA) \text{ [N]}$$

Table 34 shows this thesis test results compared with the Eurocode 5 plug shear formulation and the new formulation for plug shear failure. Mean values for C30 were used when calculating according to Eurocode. The mean differences for the new formulation were around 13% and for Eurocodes formulation around 26%. The low mean scatter at only 13% shows that the variables used in the formulations could be well suited to predict plug shear failure.

Table 34: All the plug shear series with test results, Eurocode plug shear formulation and the new formulation (R_{plug}) results.

Series	F_u [kN]	EC 5 [kN]	ABS Diff EC 5 [%]	R_{plug} [kN]	ABS Diff R_{plug} [%]
1p-5-n40	111,2	153	27	125	11
10p-5-n40	98,6	140	29,3	110	10,4
10p-5-n60	102,8	144	28,6	120	14,5
13p-5-n40	81,2	101	19,9	71	15,2
14p-5-n40	100,4	143	29,6	93	7,6
15p-5-n40	71,5	92	22,5	60	20,7

Three graphs are presented below where the length of the nailed area is varied on the x-axis , including the edge distance set to 80mm. The different lines represent different width of the nailed area, varying from 100 to 350mm with 50mm steps. The resistance according to the new formulation for plug shear is displayed on the y-axis. Characteristic value for C30 density, 380kg/m^3 is used. These figures could serve as design graphs when the nail density is around 600mm^2/nail and lower to estimate the plug shear resistance of a proposed joint with known nailed length and width.

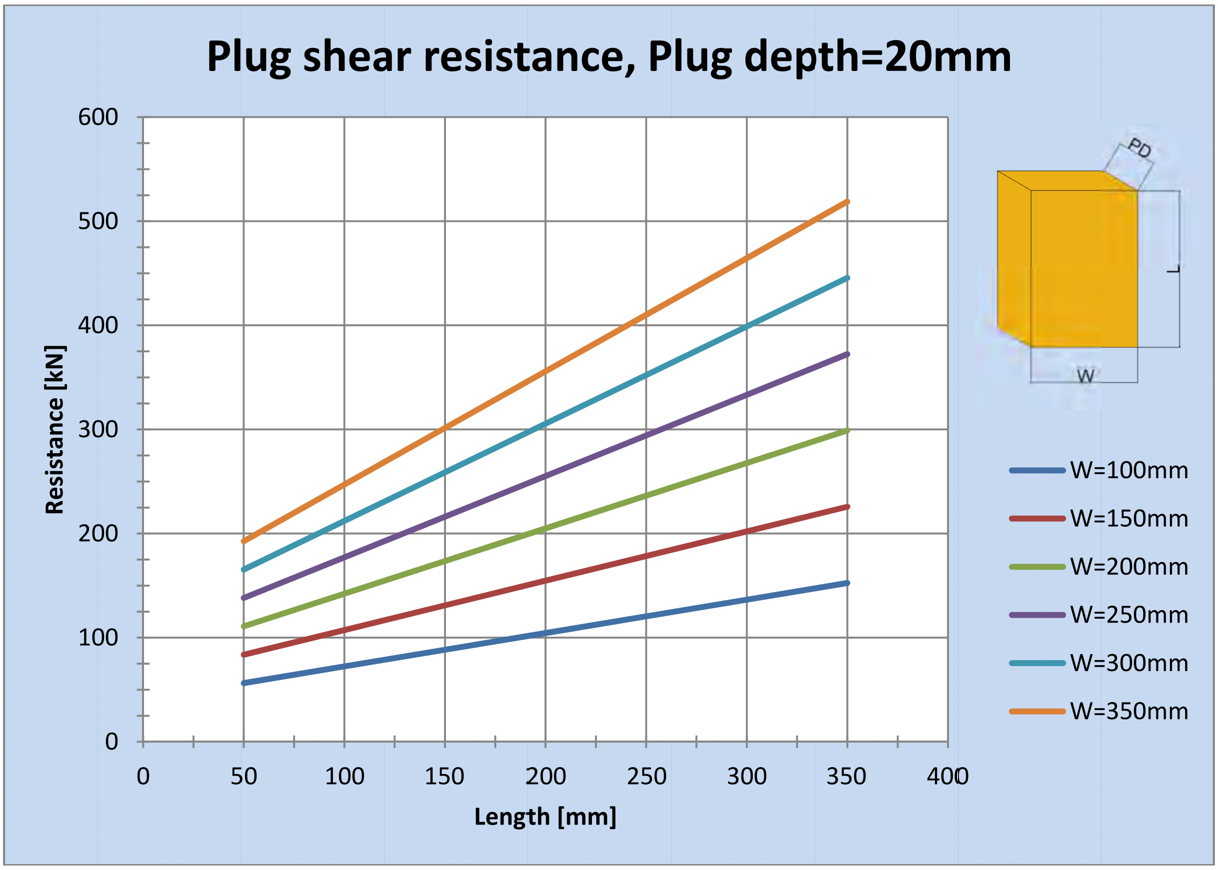


Figure 36: Plug shear resistance according to the new formulation with ρ=380kg/m^3 and plug depth (PD) equal to 20mm.

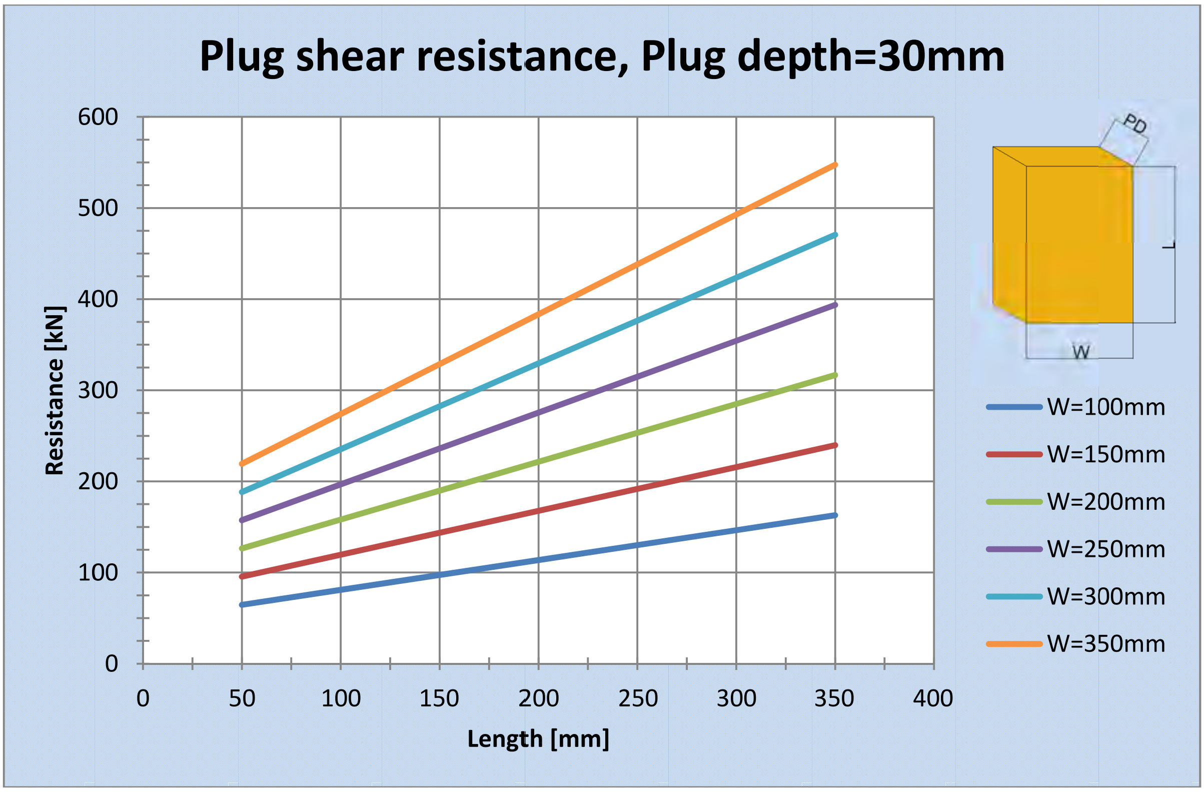


Figure 37: Plug shear resistance according to the new formulation with ρ=380kg/m^3 and plug depth (PD) equal to 30mm.

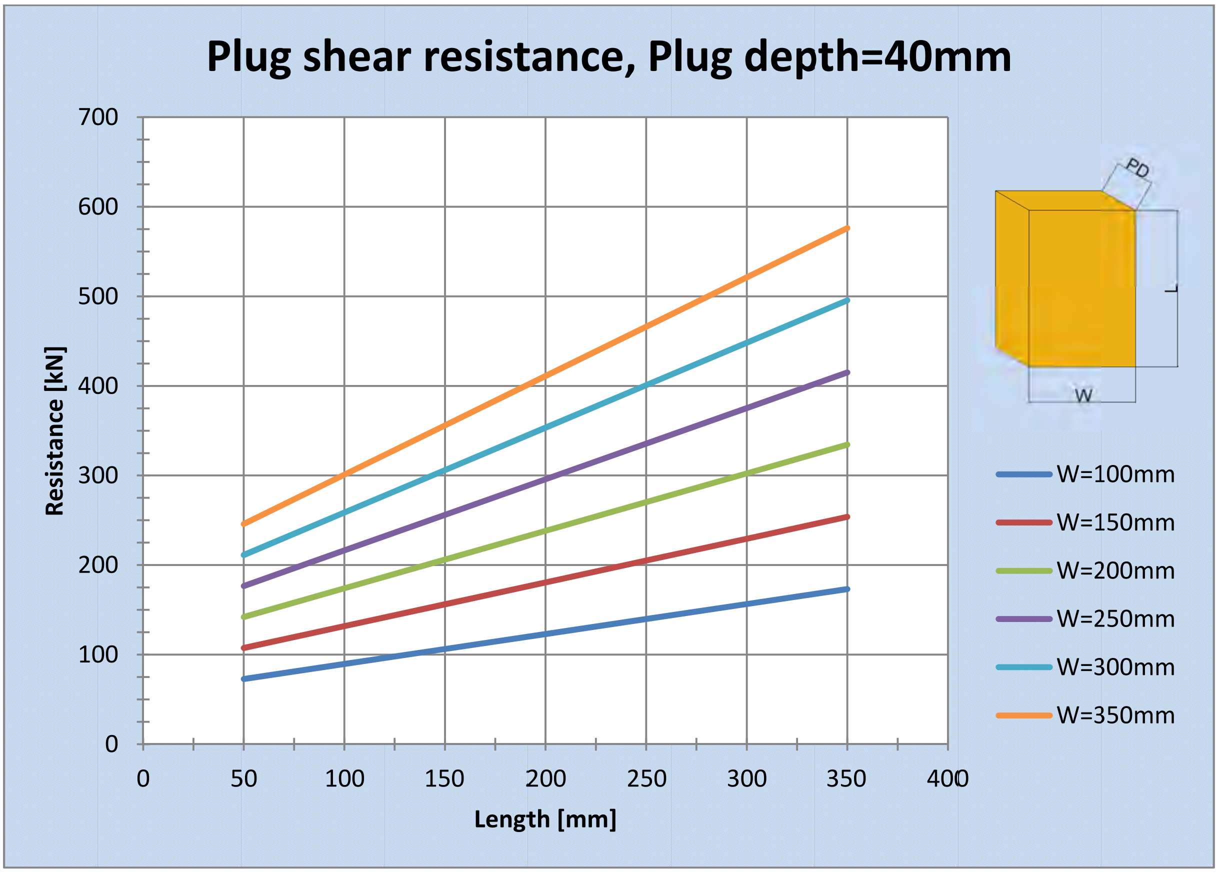


Figure 38: Plug shear resistance according to the new formulation with ρ=380kg/m^3 and plug depth equal (PD) to 40mm.

Analysis – the stiffness theory

As explained in chapter 2.4.3, observations of the plug shear tests led to the assumption that the load was taken unevenly between the different faces of the plug. Table 35 shows tests results from three independent experimental testing programs compared with the resistance according to the stiffness theory. The mean difference for all series was around 15%. When characteristic values are used to calculate the resistance almost all series are below or close to the real value from the tests, see table 36.

Table 35: Test results from three independent data sets compared to the stiffness theory, mean values used for timber's properties. H1-H14 are tests from Johansson [3] and Gir-L6, Gir-T5 are tests from Girhammar[8].

ID	Test Results [kN]	Diff [%]	R_{ST} [kN]
H1	88,4	11,6	99,9
H2	161,6	19,8	201,4
H3	250,4	5,4	264,8
H4	200,4	24,3	264,8
H5	256,8	3,0	264,8
H6	255,2	3,6	264,8
H7	181,2	18,9	223,4
H8	217,4	13,2	250,4
H9	229,0	24,8	304,4
H10	98,8	9,0	108,5
H11	177,7	7,9	193,0
H12	292,7	-2,7	285,0
H13	253,2	-13,5	223,0
H14	144,7	28,2	201,4
1p-5-n40	111,2	14,3	129,7
10p-5-n40	98,6	24,2	130,1
10p-5-n60	102,8	27,5	141,9
13p-5-n40	81,2	-12,7	72,1
14p-5-n40	100,4	2,8	103,3
15p-5-n40	71,5	-19,2	60,0
1py-5-n40	81,5	25,2	109,0
3py-5-n40	57,0	9,4	62,9
7py-5-n40	67,8	18,4	83,2
Gir-L6	185,2	17,5	224,5
Gir-T5	85,9	28,5	120,2

Table 36: Test results from three independent data sets compared to the stiffness theory, characteristic values used for timber's properties. H1-H14 are tests from Johansson [3] and Gir-L6, Gir-T5 are tests from Girhammar[8].

ID	Test Results [kN]	Diff [%]	R_{ST} [kN]
H1	88,4	-14,7	77,0
H2	161,6	-4,2	155,2
H3	250,4	-22,6	204,2
H4	200,4	1,9	204,2
H5	256,8	-25,8	204,2
H6	255,2	-25,0	204,2
H7	181,2	-5,3	172,2
H8	217,4	-12,6	193,1
H9	229,0	2,5	234,8
H10	98,8	-18,1	83,6
H11	177,7	-19,5	148,6
H12	292,7	-33,2	219,8
H13	253,2	-47,3	171,9
H14	144,7	6,8	155,2
1p-5-n40	111,2	-14,3	97,3
10p-5-n40	98,6	-1,1	97,5
10p-5-n60	102,8	3,4	106,4
13p-5-n40	81,2	-50,2	54,1
14p-5-n40	100,4	-29,6	77,4
15p-5-n40	71,5	-58,9	45,0
1py-5-n40	81,5	-7,2	172,8
3py-5-n40	57,0	7,2	92,6
7py-5-n40	67,8	0,3	81,7
Gir-L6	185,2	-20,9	47,2
Gir-T5	85,9	-8,7	62,4

If the stiffness theory was applied to bottom shear area instead the resistance for all the tests performed was 2-3 times higher than the failure load. If the tension side is to fail first as assumed, the bottom face will take the entire load and will fail shortly thereafter. Figure 39 depicts the resistance according to the stiffness theory. Each line represents a certain nailed width of the joint ranging from 50 to 500mm in 50mm steps. In the x-axis the nailed length is varied. The graph is valid for plug depth of 22mm, which means a penetration depth of around 33mm.

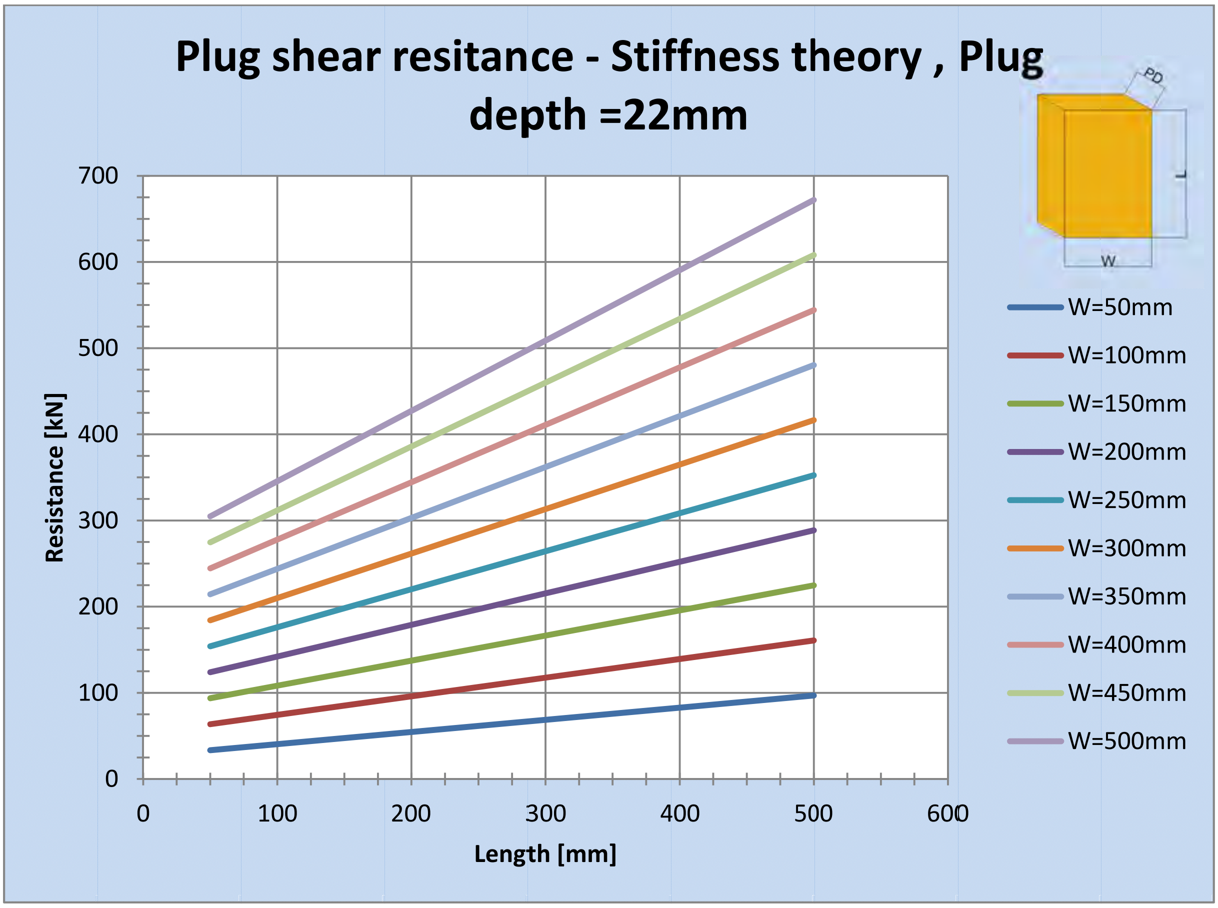


Figure 39: Plug shear resistance according to the stiffness theory, mean values used for the timbers strength and stiffness properties. W is the nailed width, L the nailed length including the edge distance.

Figure 40-45 shows six different surface plots depicting the stiffness theory with mean, characteristic and characteristic values times 0,7. The resistance [kN] is plotted on the z-axis, the load taken by the tension face, alpha (%), on the y-axis, and the tension area [mm^2] on the x-axis. Two different angles are presented for each set of plot. The accuracy of the stiffness theory compared to the test results is visible in figure 40 and 41. Fig 44 and 45 shows that if one would implement an suggestive safety factor to the stiffness theory with characteristic value, the theory is on the safe side because all test results are above the gray surface.

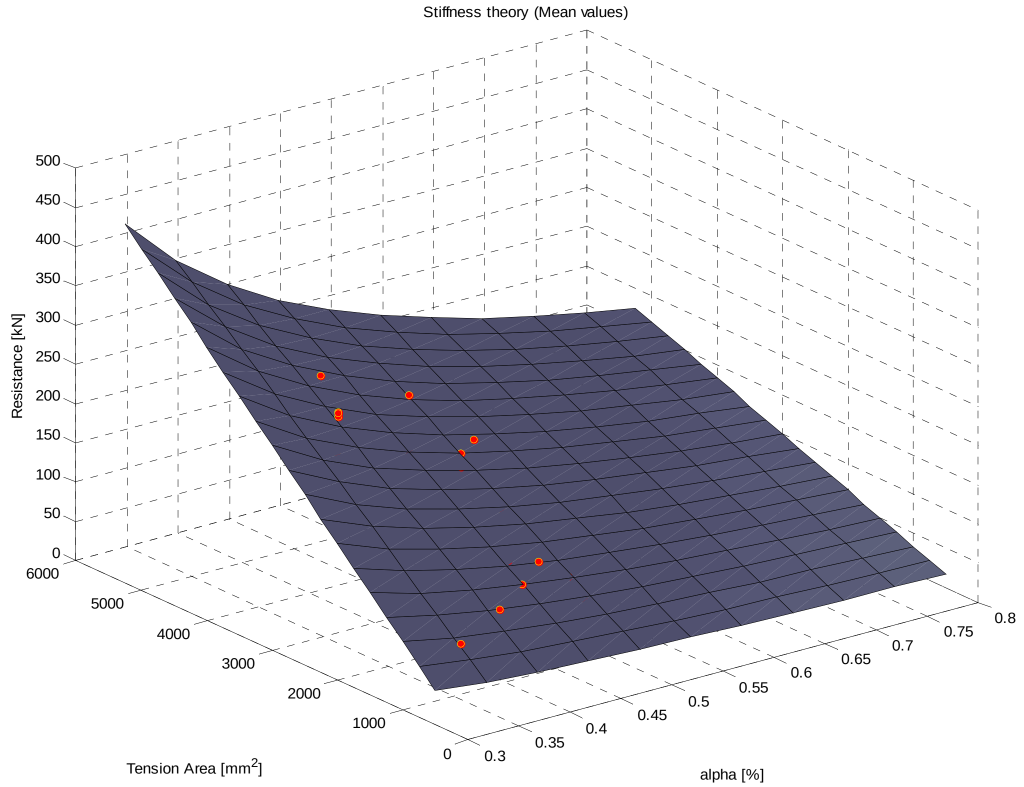


Figure 40: Surface plot (Angle 1) of the stiffness theory with test results as dots, dark area is the stiffness theory using mean values as input, dots represent test results from see table 35.

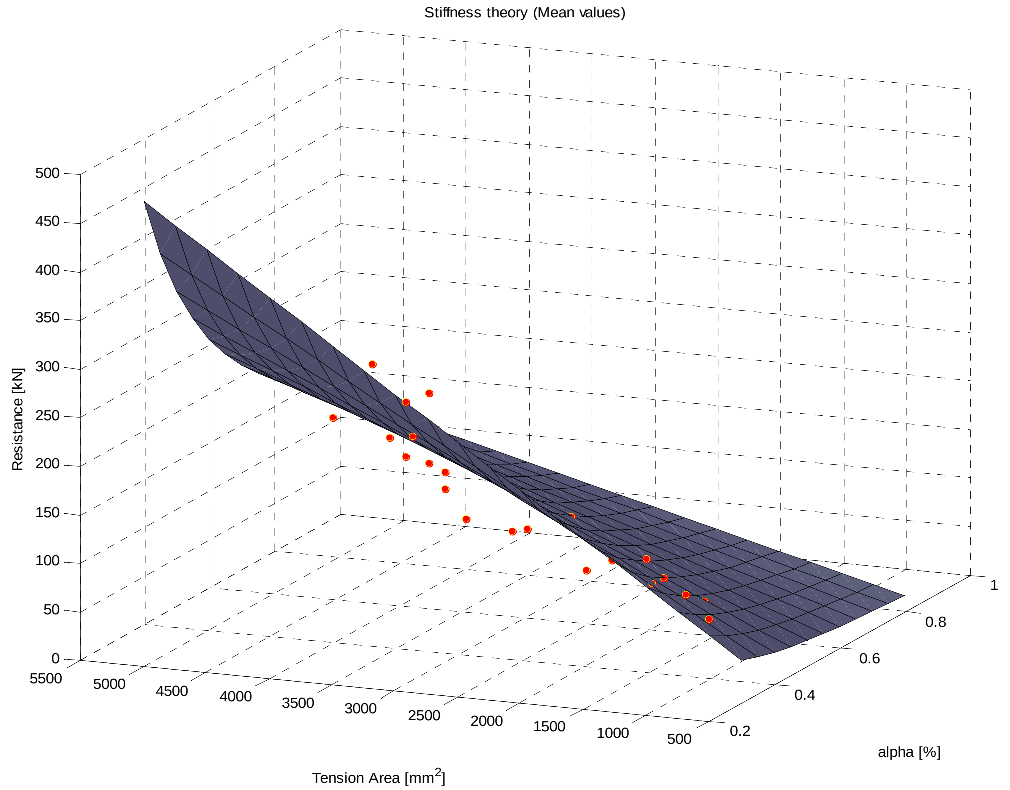


Figure 41: Surface plot (Angle 2) of the stiffness theory with test results as dots, dark area is the stiffness theory using mean values as input, dots represent test results from see table 35.

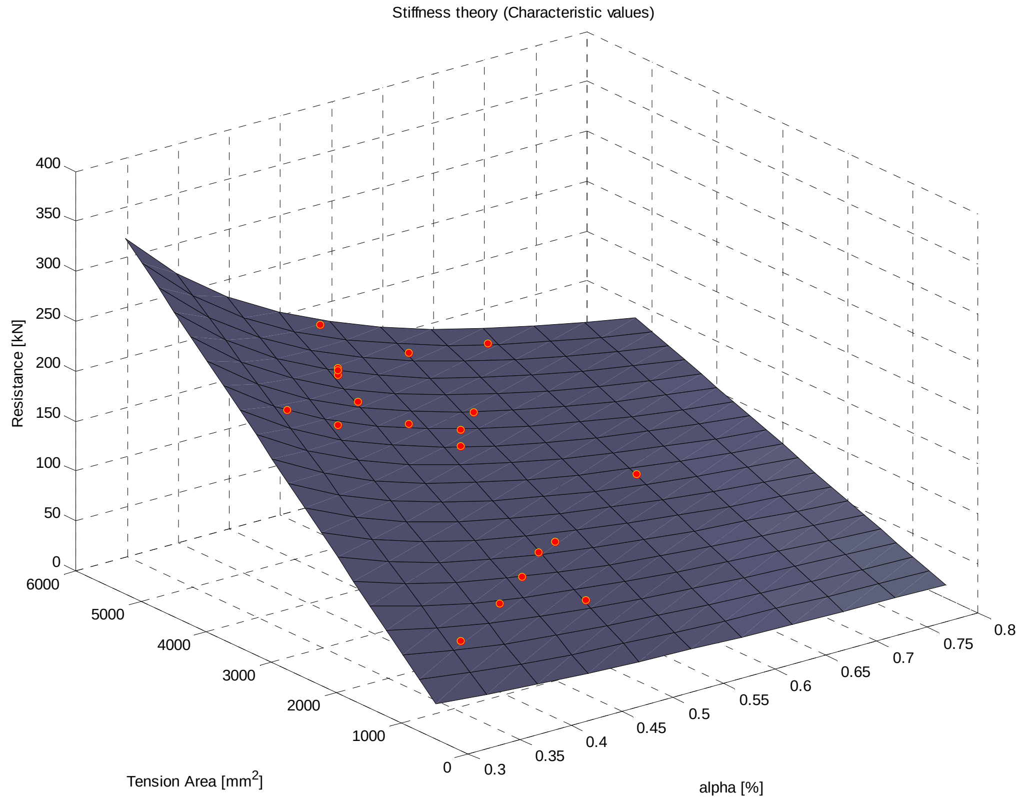


Figure 42: Surface plot (Angle 1) of the stiffness theory with test results as dots, dark area is the stiffness theory using characteristic values as input, dots represent test results from see table 36.

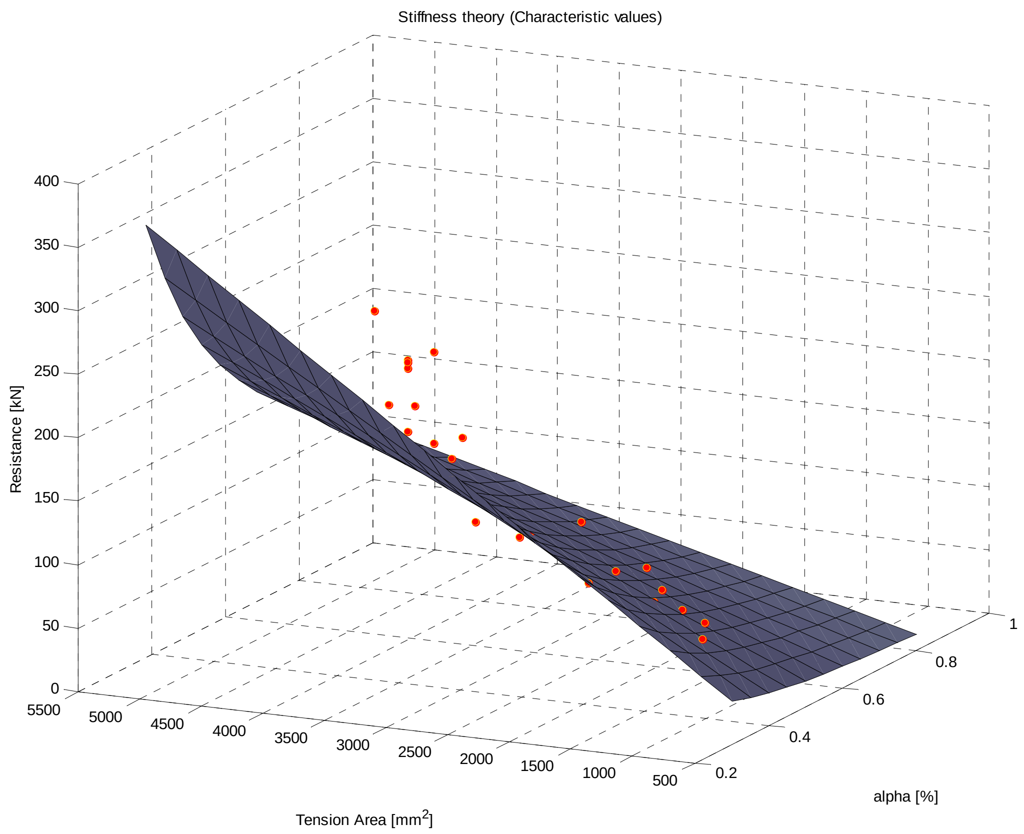


Figure 43: Surface plot (Angle 2) of the stiffness theory with test results as dots, dark area is the stiffness theory using characteristic values as input, dots represent test results from see table 36.

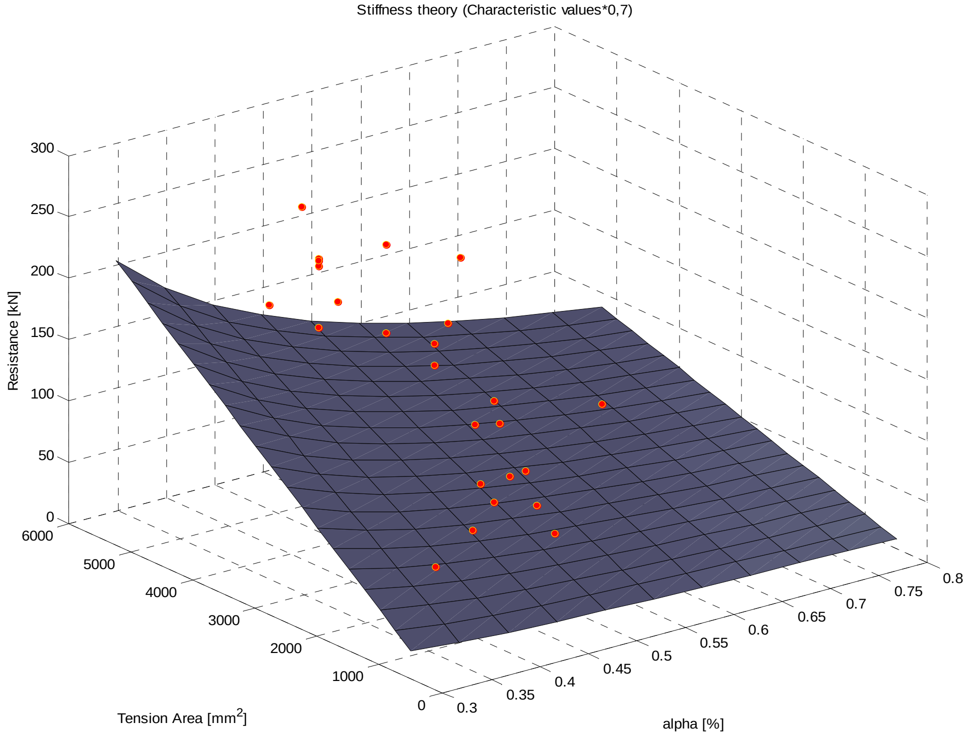


Figure 44: Surface plot (Angle 1) of the stiffness theory with test results as dots, dark area is the stiffness theory using characteristic values multiplied by 0,7 as input, dots represent test results from see table 36.

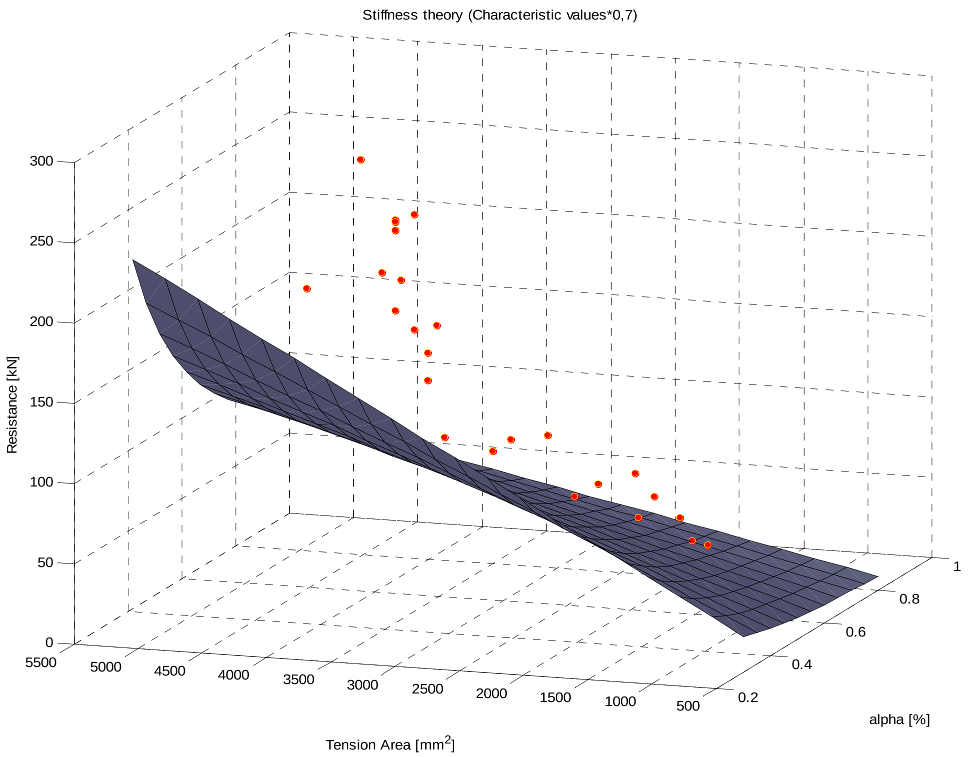


Figure 45: Surface plot (Angle 2) of the stiffness theory with test results as dots, dark area is the stiffness theory using characteristic values multiplied by 0,7 as input, dots represent test results from see table 36.

Conclusion plug shear results

- The density of the timber seems to influence the resistance of plug shear failure in some plug shear series. Other factors that could have affected the results are knots and local weaknesses in the timber.

- Penetration depth increase from 33mm to 53mm only increased the plug depth by an average of 5mm. The two series 10p-5-n40 and 10p-5-n60 had the same nail configuration but different nail length and had almost the same mean failure load.

- When the nail density reached around 600-700mm^2/nail or lower plug shear failure starts to occur in the test series.

- The formulation for plug shear in Eurocode overestimates the resistance for the tests performed in this thesis when using mean values for C30. The mean difference was +26%. The mean difference for the new formulation was around 13% both overestimating and underestimating.

- The stiffness theory which was proposed after observing the plug shear tests proved to be accurate when compared to the plug shear results from this thesis, Johansson's [3] report and Girhammar's [8] report.

5 Discussion

The analysis of the ductile results showed that a joint with a steel plate close to the thin border could have the same resistance if compared to a joint with the same nail pattern but with a thick plate instead. It's interesting that even though the plate had a thickness of 2.5mm, which is 0.5mm away from the thin border, it still acted as a thick plate when it came to the locations of the plastic hinges that were formed in the nails. If anything, it would be more expected if the plate acted as a thin one which was not the case for all the joints that were tested.

For the plug shear tests a difficult part of the work was to determine what really happened when the specimens failed. What parts of the timber were involved in the initial load drop and more importantly why? Should there be a combination of tension and shear strength when calculating the resistances or should they be separated and let the maximum of the two decide the design value? Is the load unevenly distributed between the different shear and tension areas? Are certain areas completely uninvolved when plug shear failure occurs? All these questions were difficult to answer in this master thesis because of the general approach in the testing program. More in depth tests must be carried out on extreme nail patterns in order to better understand the failure. One thing is certain though, placement and nail density plays an important part in this kind of failure.

The border joint 7py had an unorthodox nail pattern. It was nailed as an hourglass form. Still when it failed with plug shear the side fracture lines followed the same pattern as with the other plug shear joints. This is interesting because in the other patterns the nails are nailed close to each other while in this pattern there is no "weak link" along the line of nails.

The factors that were given by the Matlab curve fit function were tricky to interpret. I still believe it was a good approach and if more detailed tests were done on plug shear joints a pattern linking the plugs geometry and the timbers strength and stiffness properties could have been discovered.

The stiffness theory proved to be accurate when compared with test data from three independent data sets regarding plug shear failure. Tests performed on more extreme nail patterns could confirm and/or help develop the stiffness theory. Test abortion and examination of the semi-failed specimen after each major load drop could also prove useful in determining the exact fail order of the different faces.

Source of error

- Hand nailing: Because the nails were hammered manually the angle between a nail and the grain of the timber could have been non perpendicular. The upper and lower joint steel plates were not perfectly nailed in the middle of the timber element introducing an eccentricity.

- Density measurement: The density was measured for the entire specimen. For the ductile joints only the volume of wood directly under the nail is involved in the failure and therefore it’s the density that should be measured. For plug shear joints a larger volume is involved making the source of error less significant in that case.

- Local weaknesses: Almost every timber element that was used to construct a joint had knots and other local deficiencies.
- Moisture: Moisture content in the timber affects its properties. The moisture readings done in this thesis were not considered very accurate.

Future research

- Perform tests on clearwood which has less local defects than softwood minimizing a source of error. Even though knot-free timber is not how the reality looks like it will serve well when trying to develop a model for plug shear failure.

- Design geometrically extreme nail patterns that may not be realistic but will prove useful when trying to confirm new theories concerning plug shear failure.

- Aborting plug shear tests as soon as a major crack, which leads to a load drop, develops in the timber in order to analyze the different stages of failure and truly confirm which faces of the plug fail at what order.

- Usage of custom made steel plates so that both hole placements and plate thickness can be varied to a greater extent than what is available using today’s standard plates.

6 References

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[2] UNIN 1995-1-1-2009_2009_EEN (Eurocode 5).

[3] Johnsson,H. (2004). *Plug shear failure in nailed timber connections (avoiding brittle and promoting ductile failures)*. Post Doctoral Thesis, Department of Civil and Environmental Engineering, Luleå.

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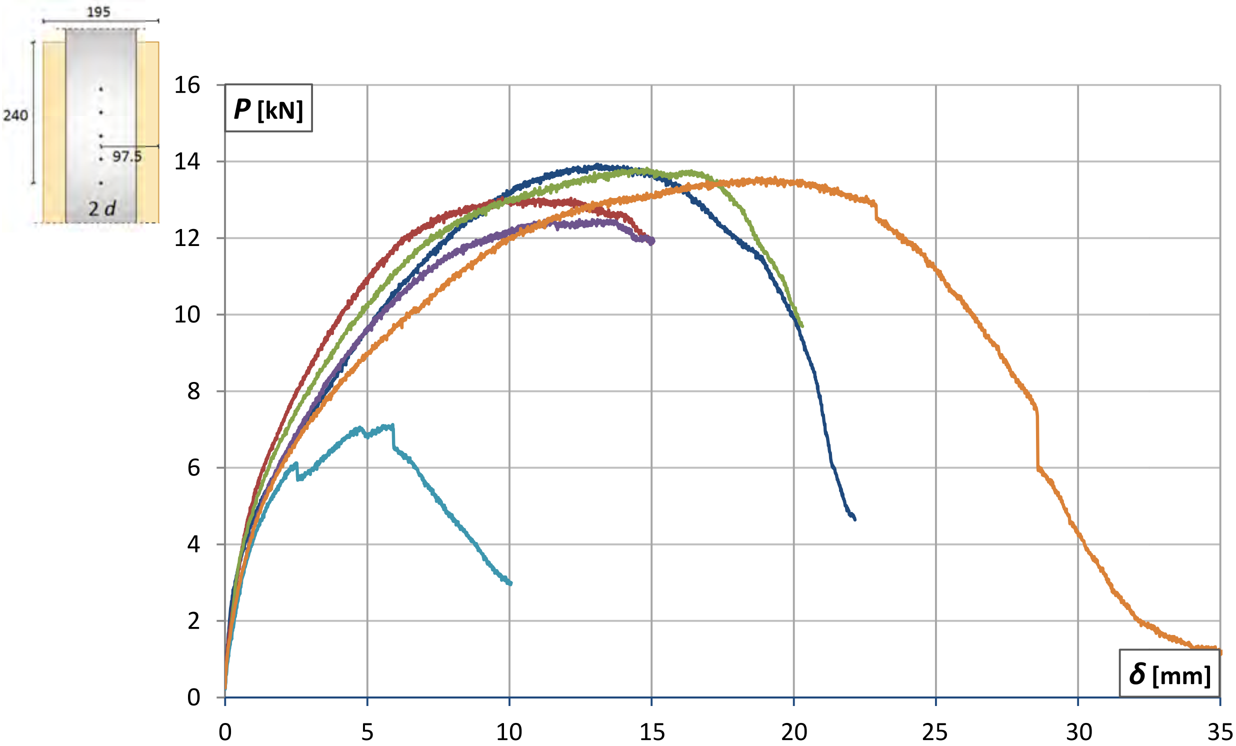
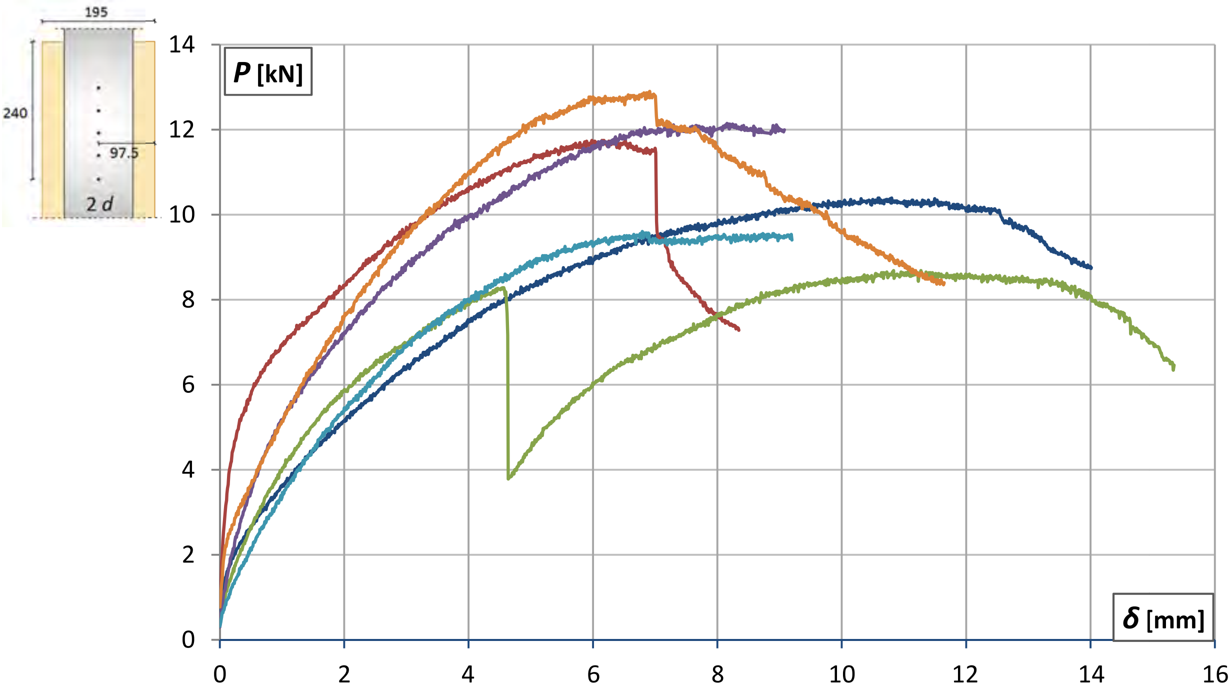
[8] Girhammar U.A (1992) Avrapportering av limträkonstruktioner. Tekniskt rapport.

Appendix A
Load displacement graphs for all series

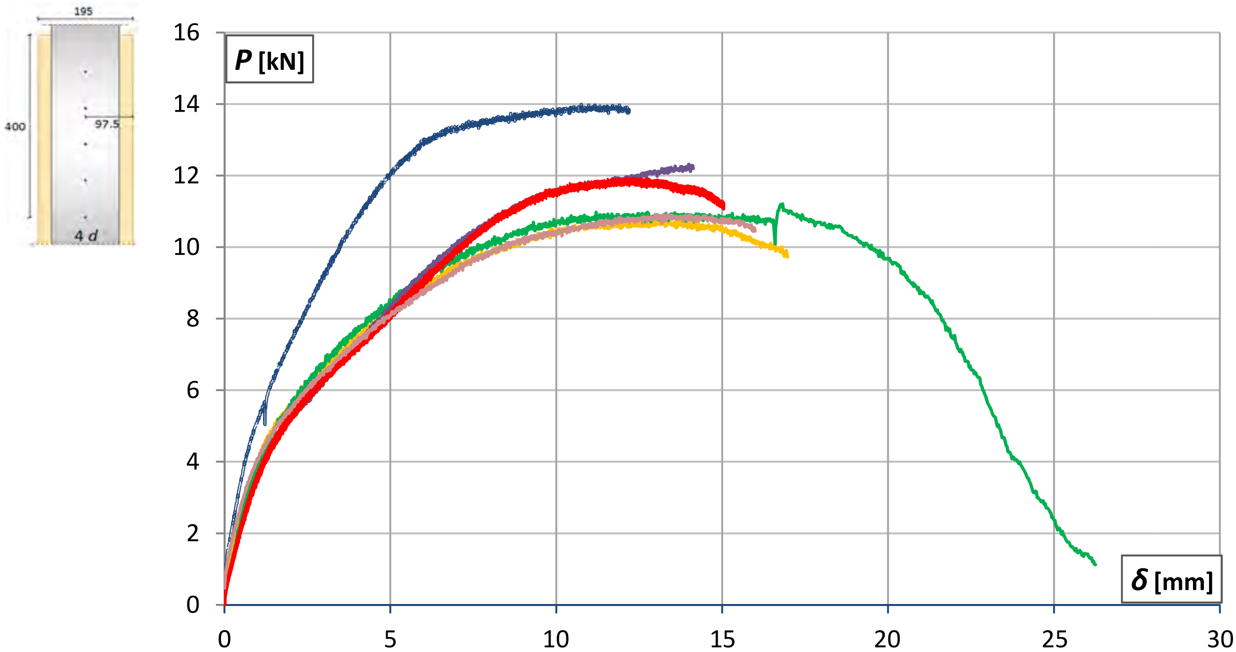
2d-2.5-n40 – nr of nails: 5



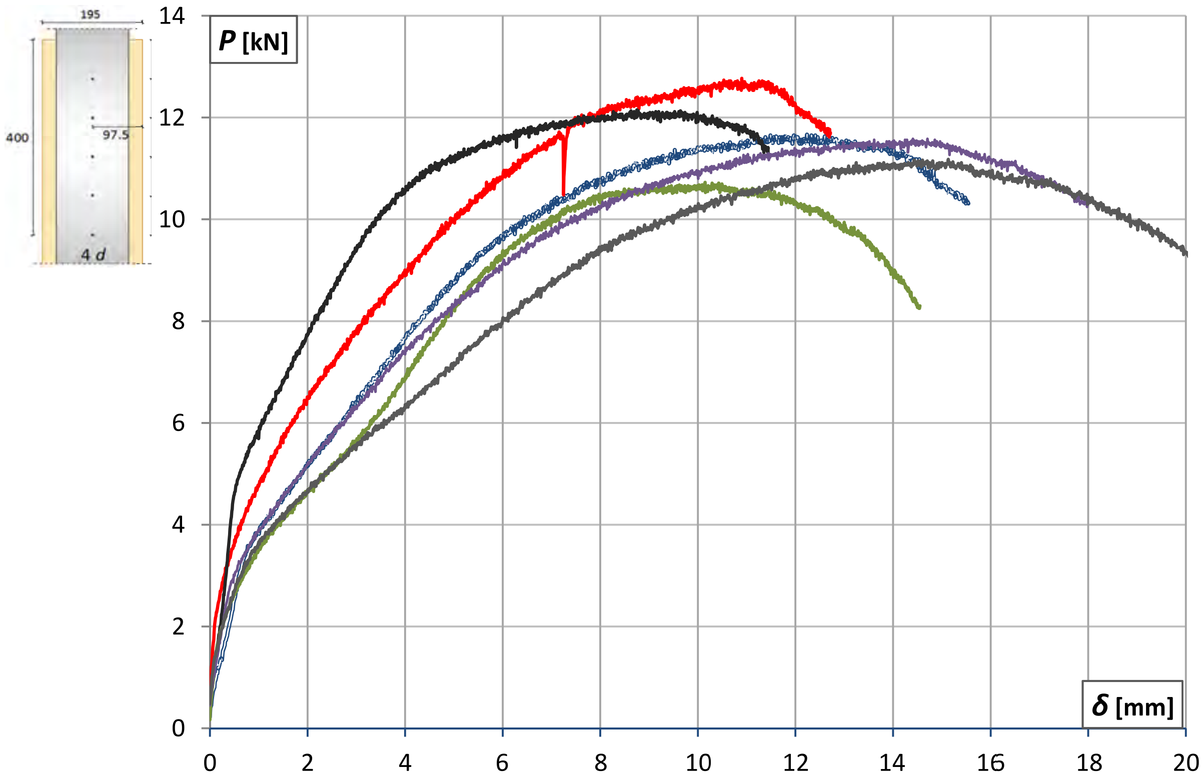
2d-5-n40 – nr of nails: 5



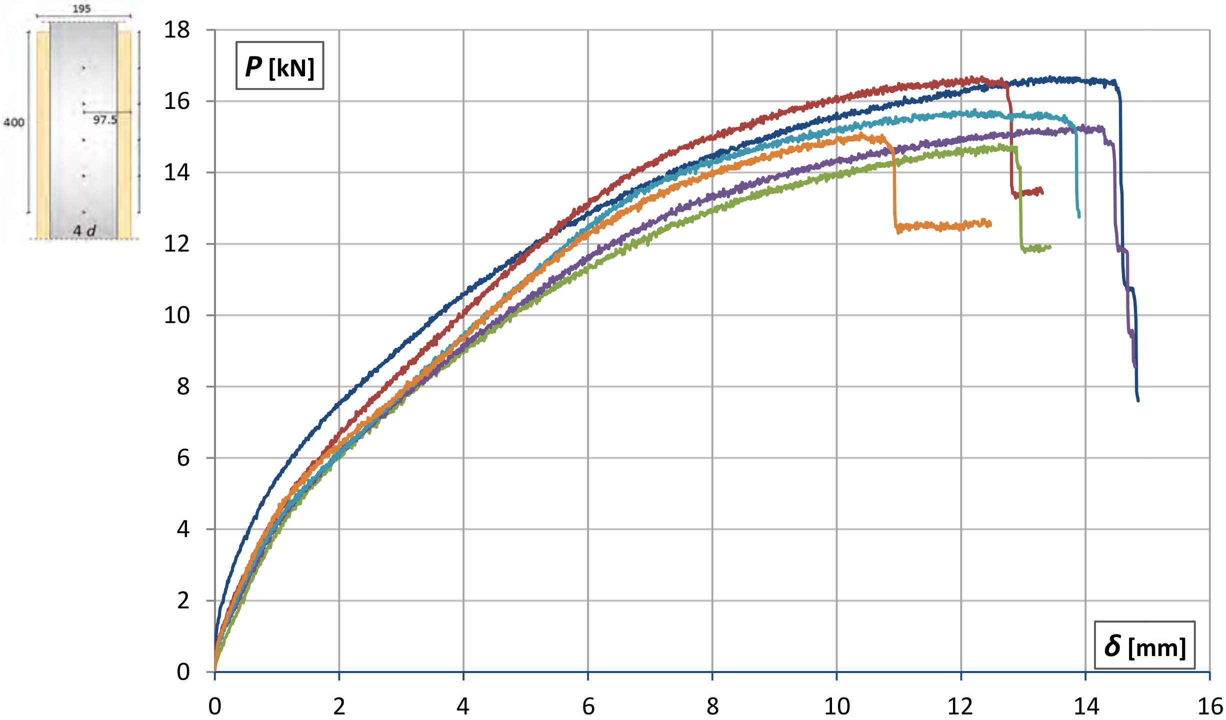
4d-2.5-n40 – nr of nails: 5



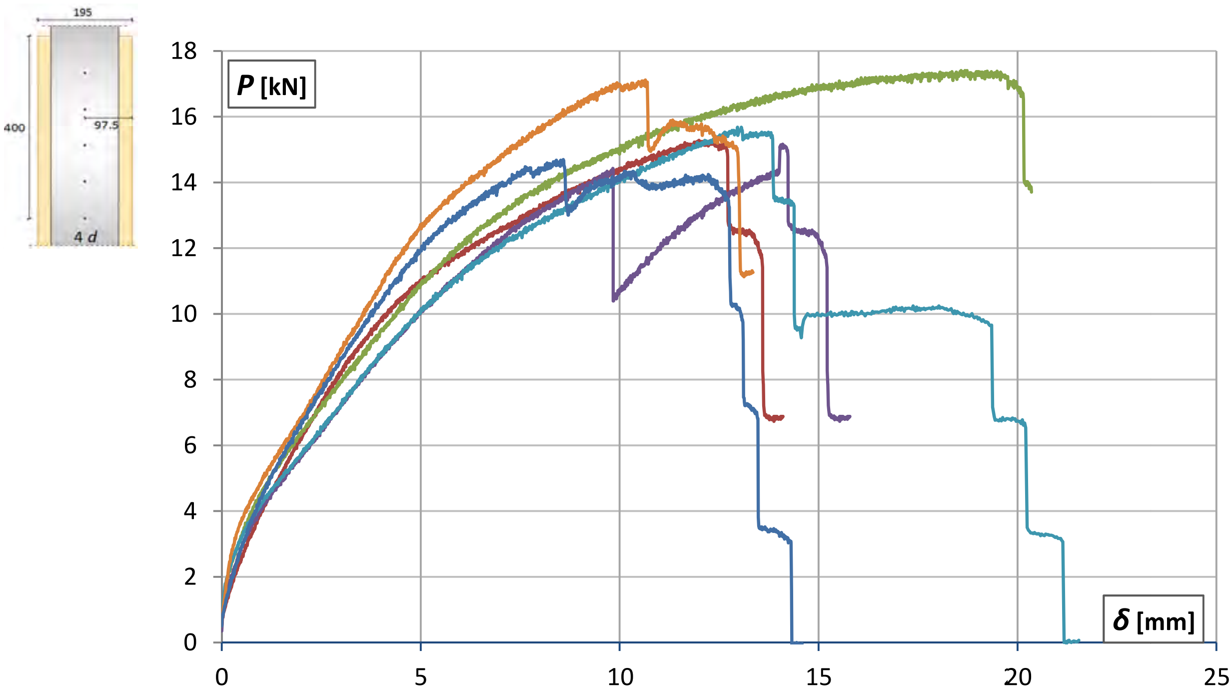
4d-5-n40 – nr of nails: 5



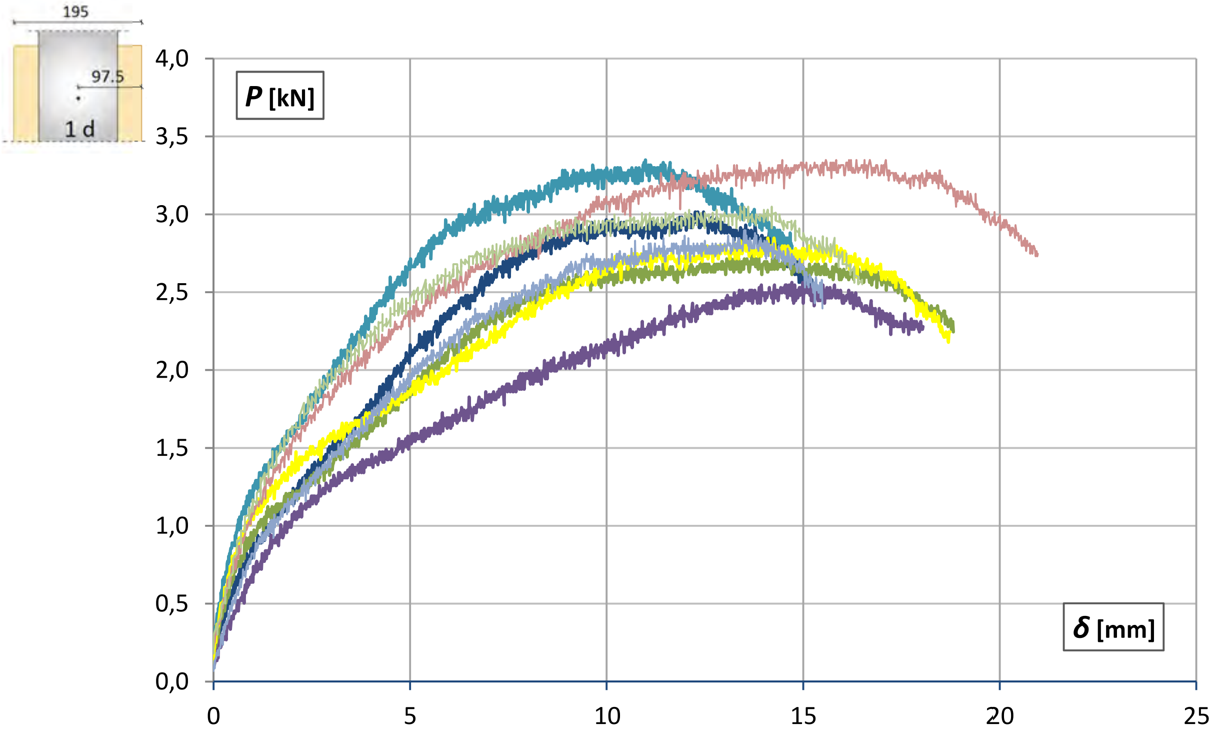
4d-2.5-n60 – nr of nails: 5



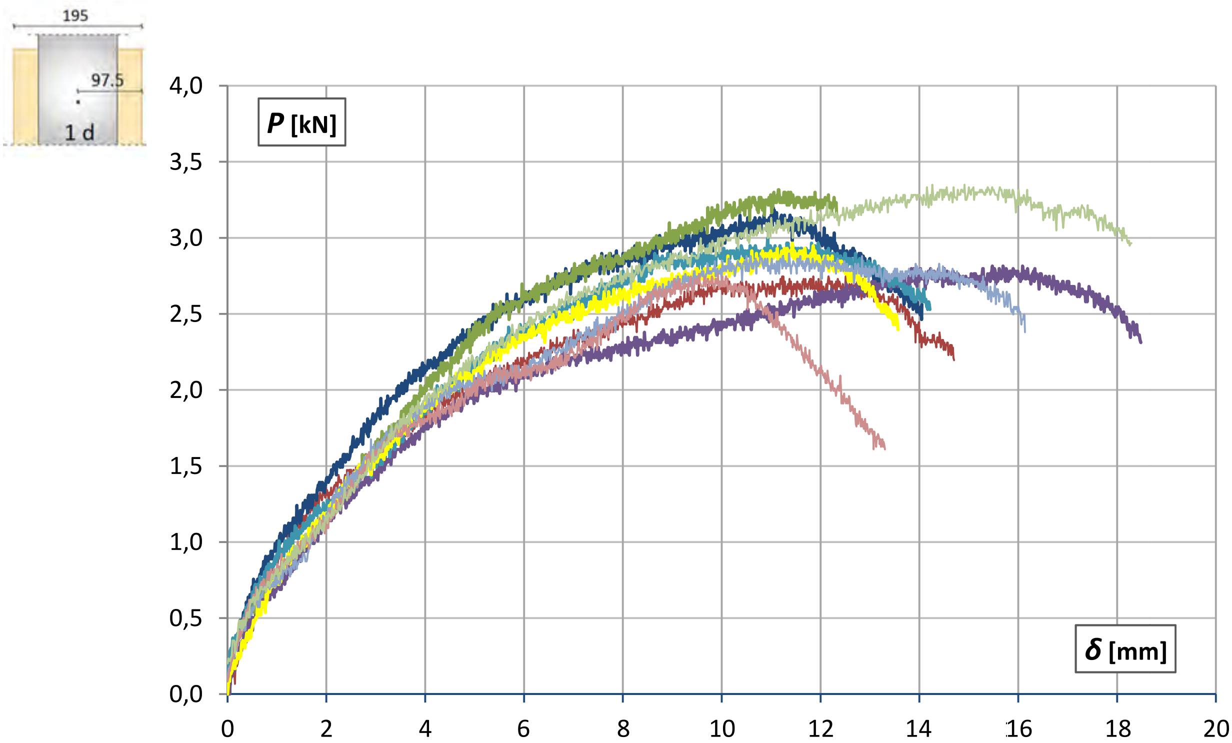
4d-5-n60 – nr of nails: 5



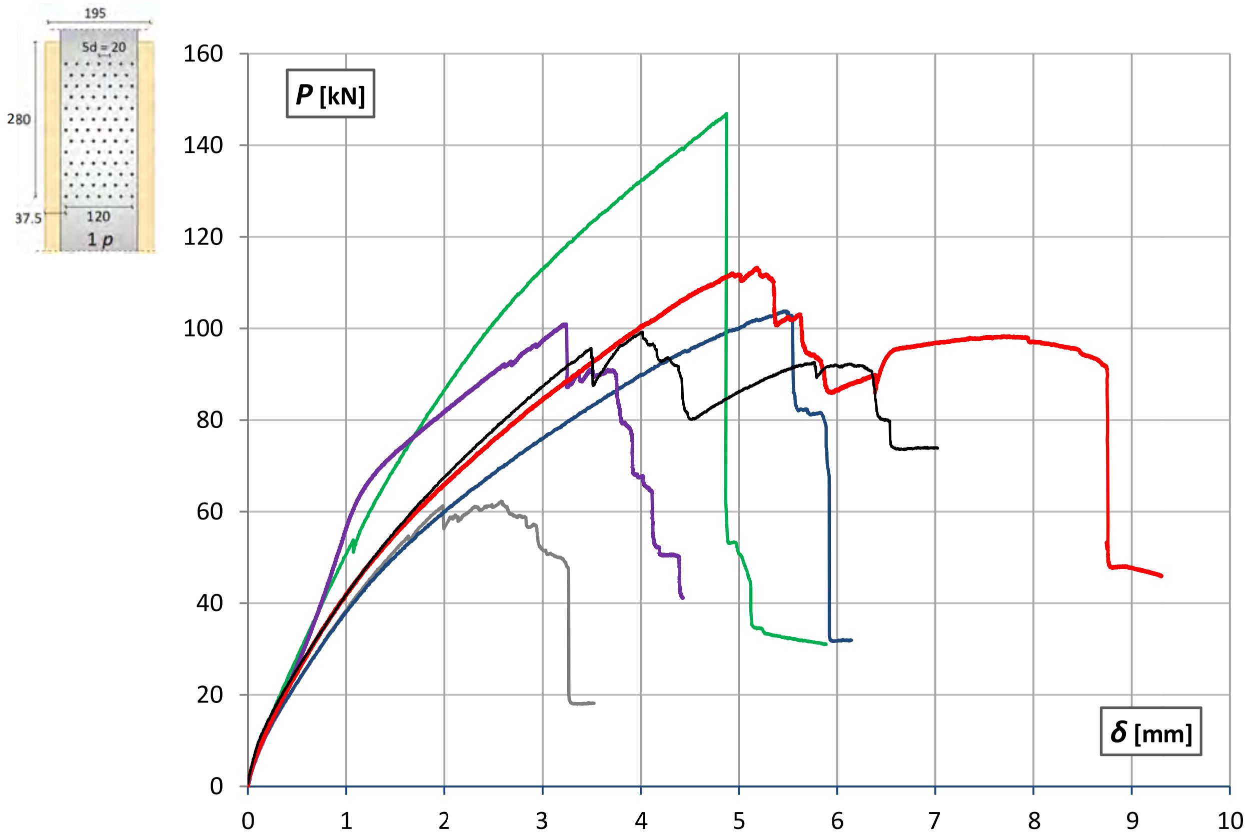
1d-2,5-n40 – nr of nails: 1



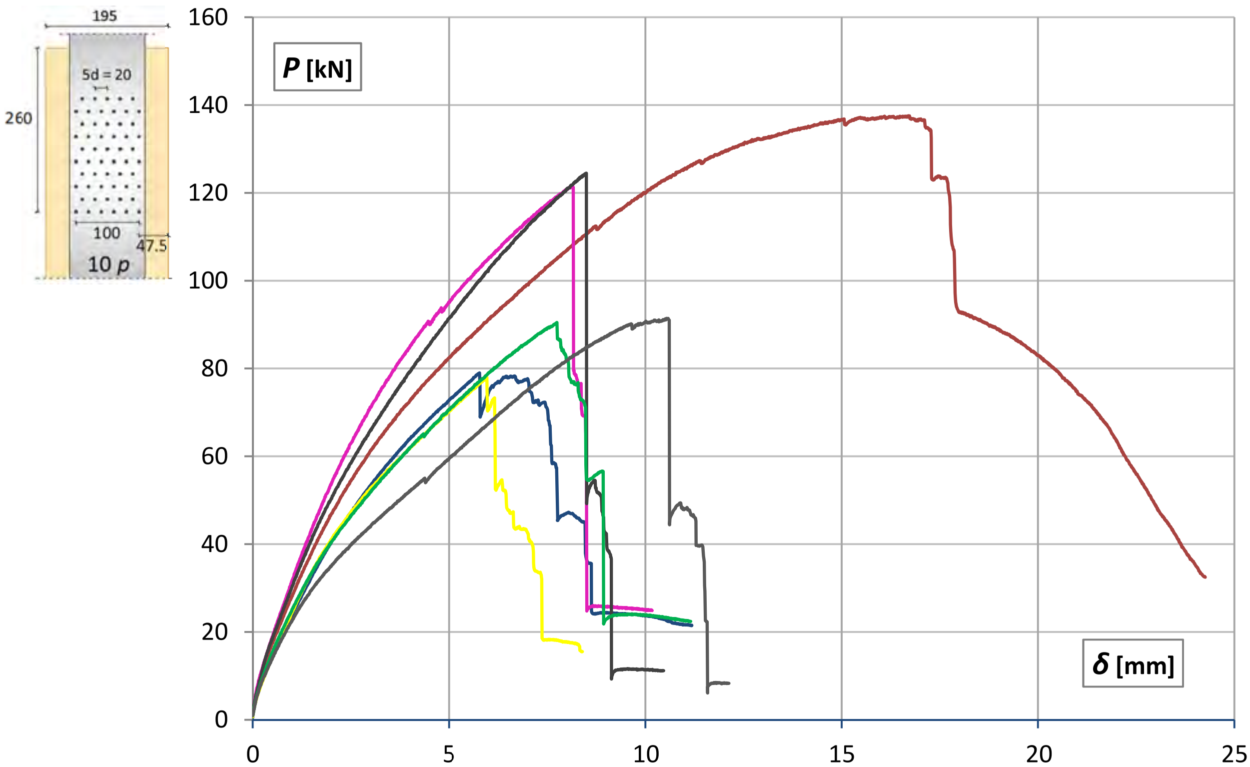
1d-5-n40 – nr of nails: 1



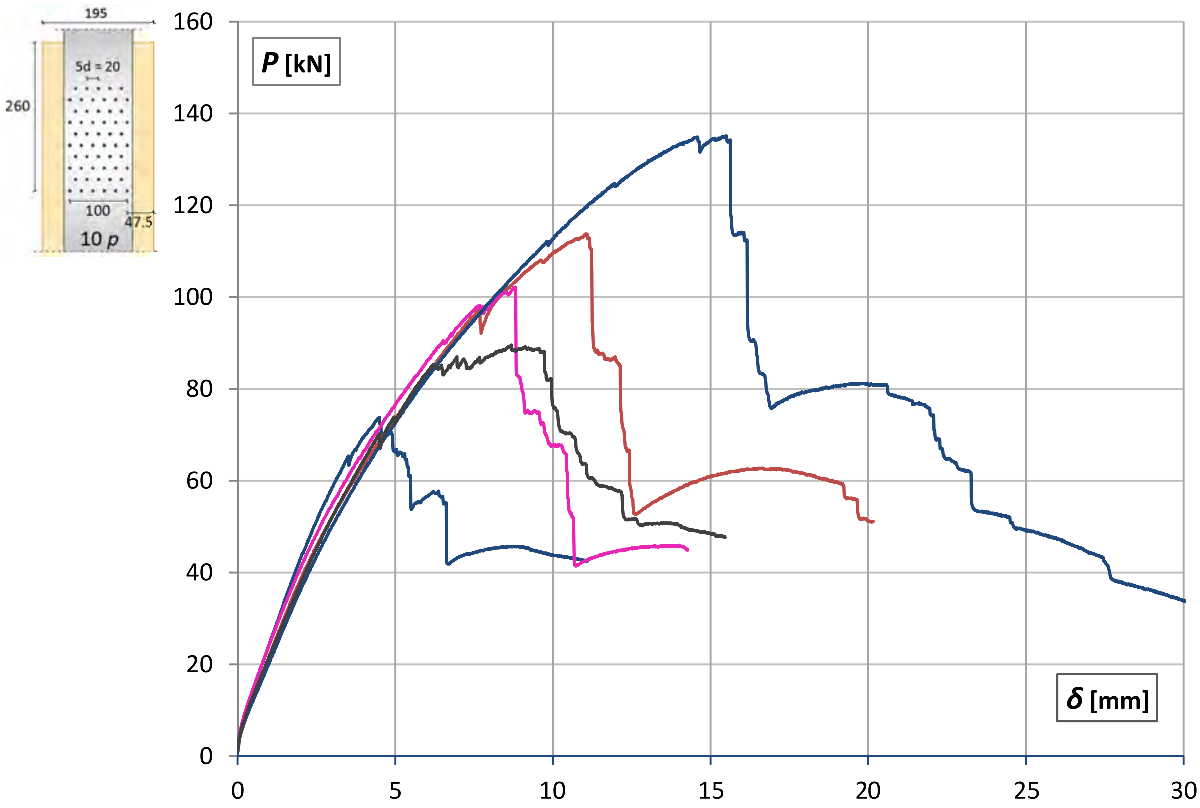
1p-5-n40 – nr of nails: 85



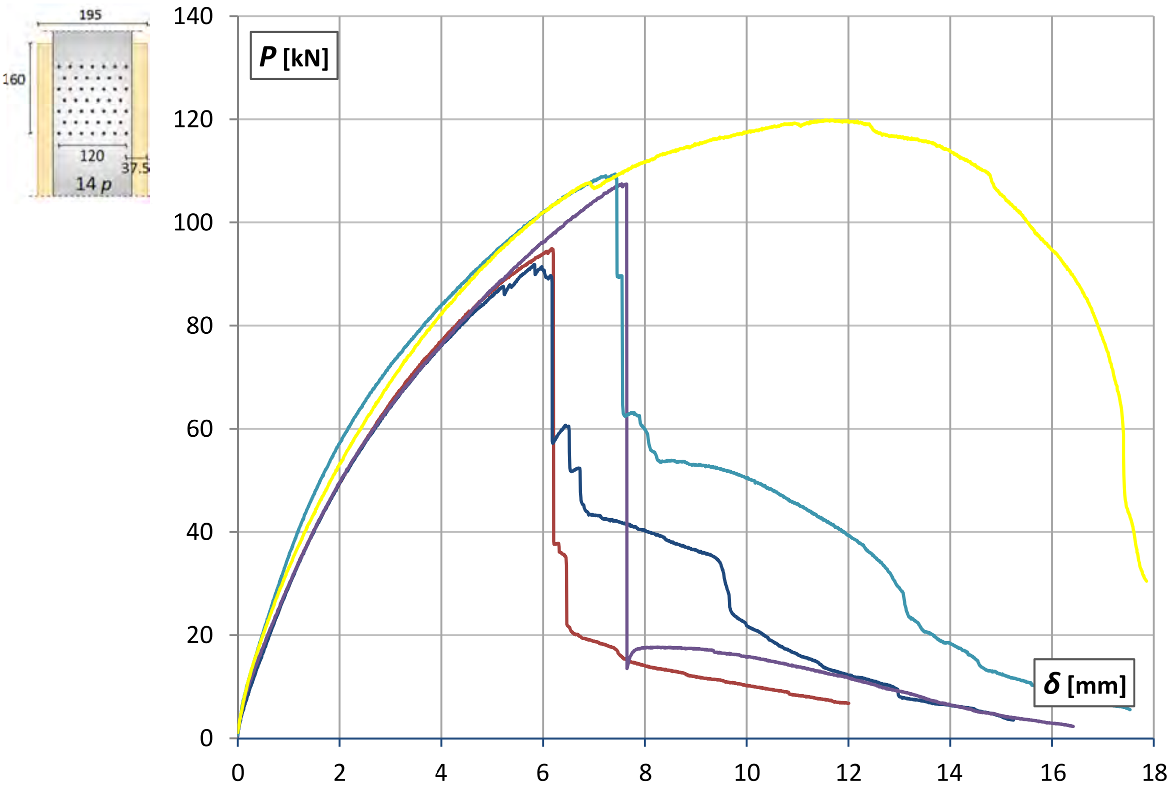
10p-5-n40 – nr of nails: 55



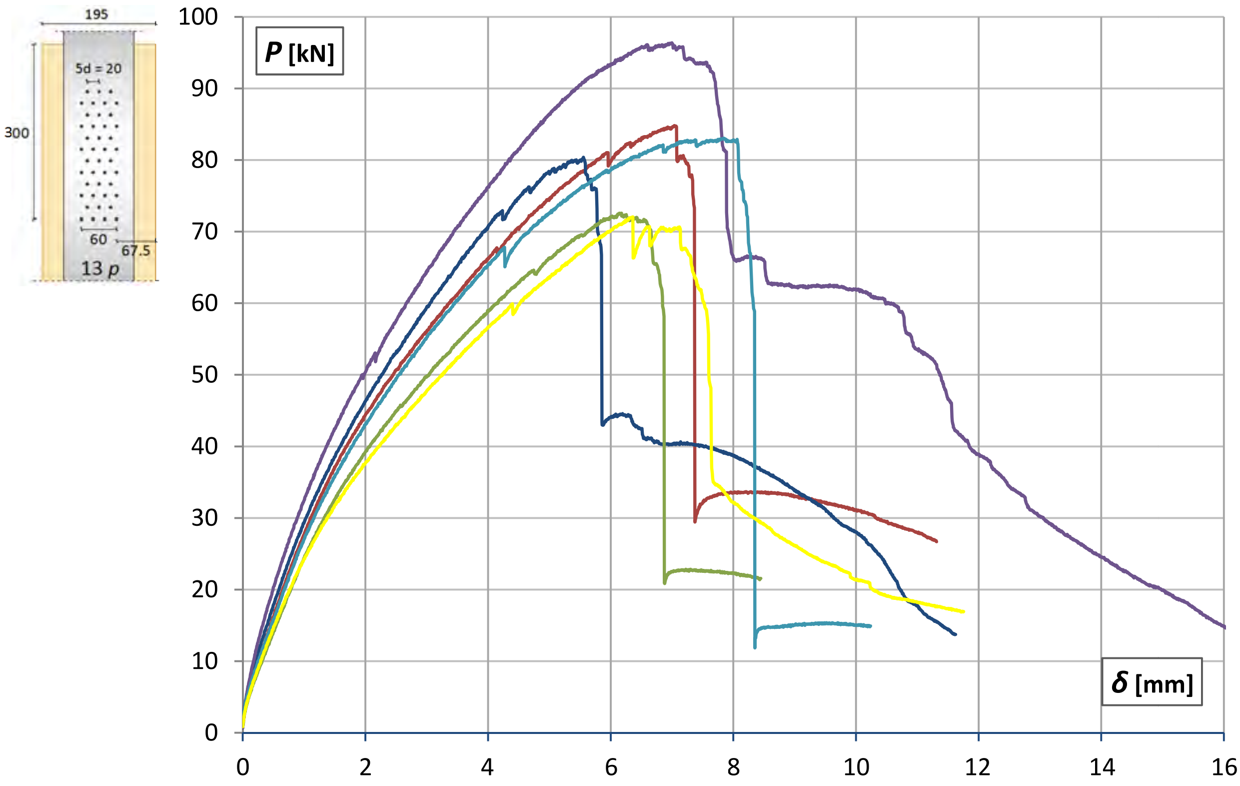
10p-5-n60 – nr of nails: 55



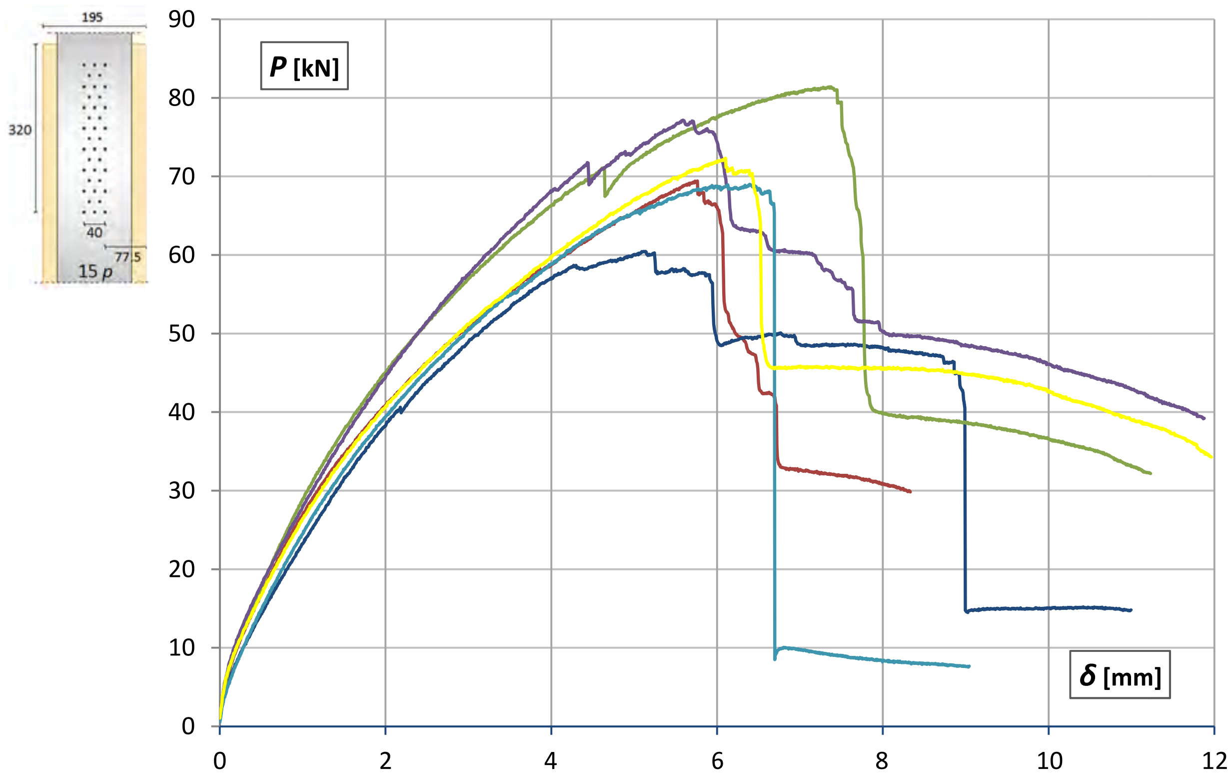
14p-5-n40 – nr of nails: 46



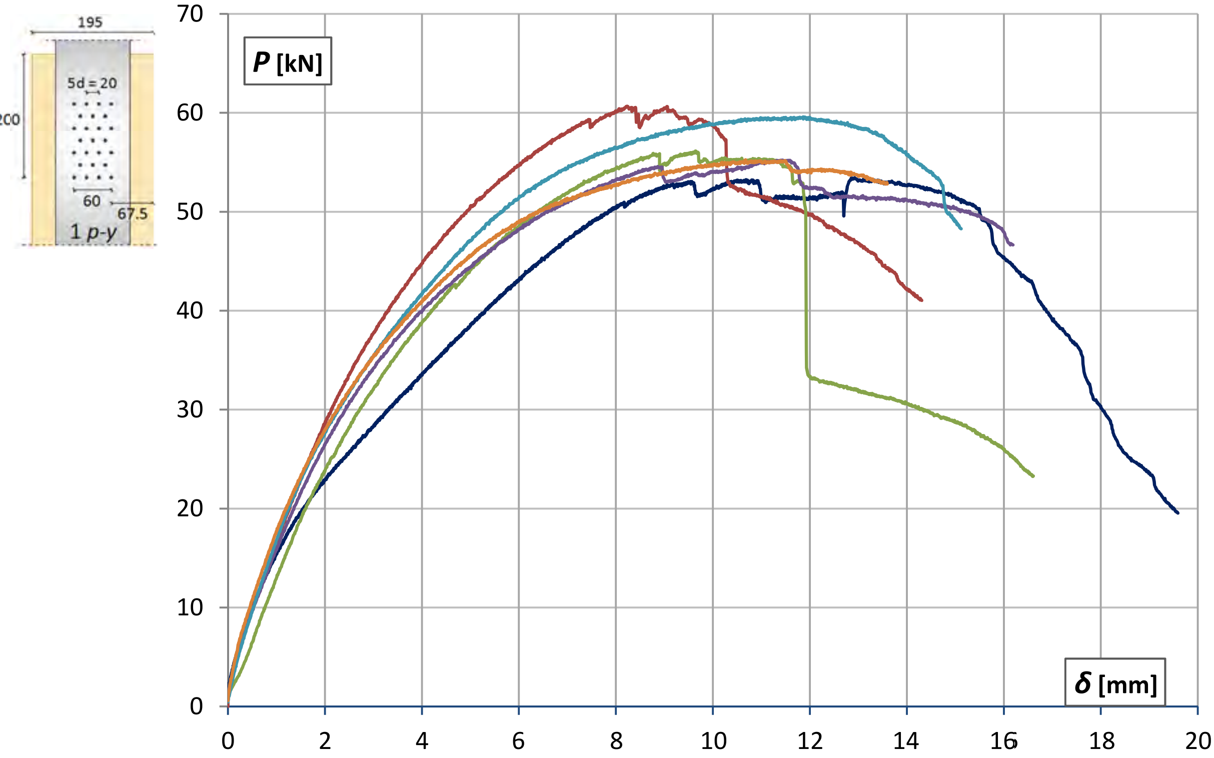
13p-5-n40 – nr of nails: 42



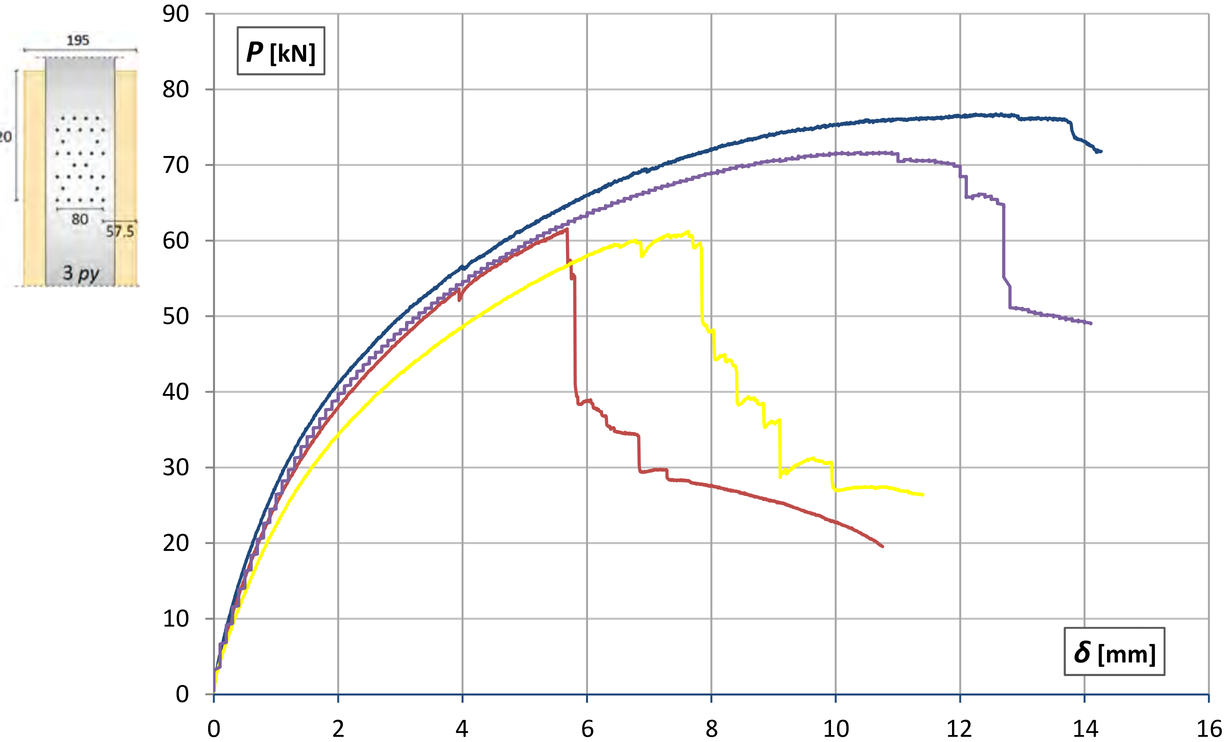
15-p-n40 – nr of nails: 38



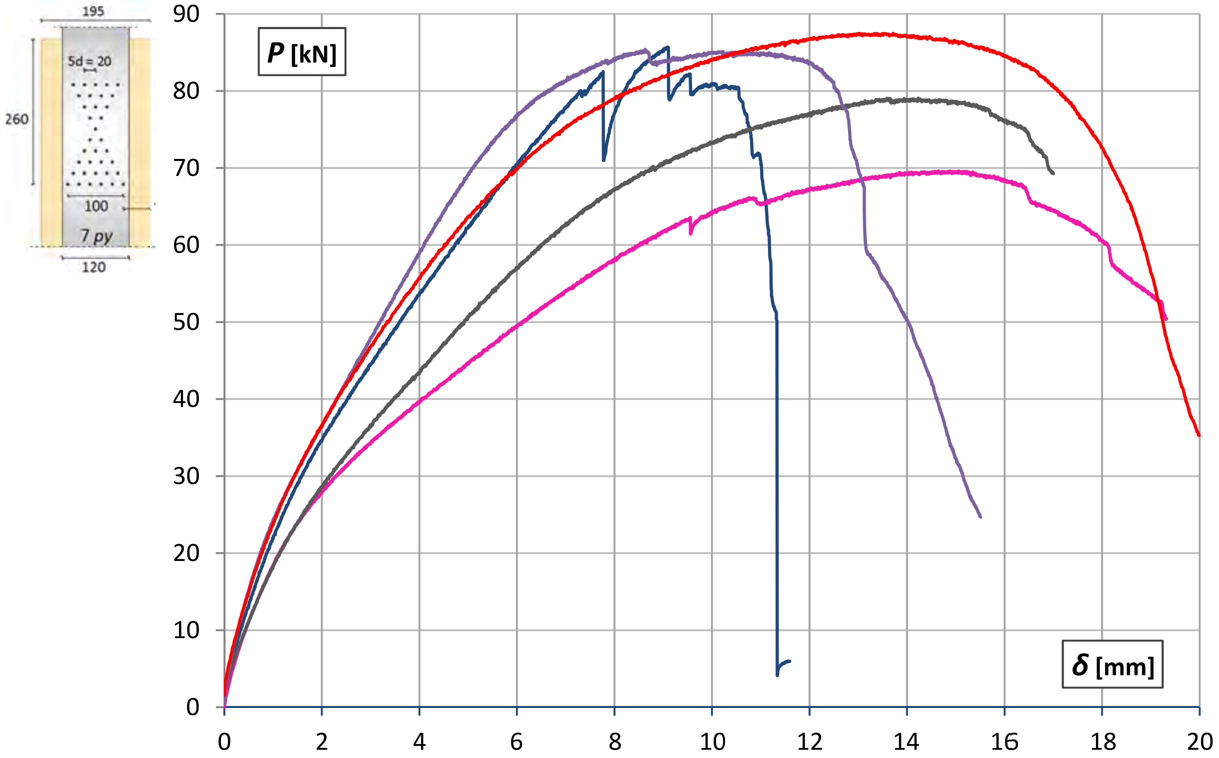
1py-5-n40 – nr of nails: 25



3py-5-n40 - – nr of nails: 30



7py-5-n40 – nr of nails: 35



Appendix B
MATLAB Joint simulation model

```
%%
clc
close all
clear all
format short
%%

prompt = {'Enter density range(min) :','Enter density range(max):','Enter
yield strength range(min) :','Enter yield strength range(max):','Enter nail
penetration length: (mm)','Enter nail diameter: (mm)','Enter plate
thickness: (mm)','Enter a1: (a1*d mm)','Enter a2: (a2*d mm)','Enter s1:
(mm)','Enter s2: (mm)','Enter number of nails: ','Enter number of
simulations:','Enter Serie ID :'};
dlg_title = 'JJS;
num_lines = 1;
def =
{'349','536','792','939','33','4','5','14','10','60','40','20','10','XX'};
options.Resize='on';
options.WindowStyle='normal';
options.Interpreter='none';
userInput = inputdlg(prompt,dlg_title,num_lines,def,options);

userDensityMin = str2num(userInput{1});
userDensityMax = str2num(userInput{2});
userFyMin = str2num(userInput{3});
userFyMax = str2num(userInput{4}); %#ok<*ST2NM>
t1 = str2num(userInput{5});
d = str2num(userInput{6}); %#ok<*ST2NM>
plate = str2double(userInput{7});
a1 = str2num(userInput{8});
a2 = str2num(userInput{9});
s1 = str2num(userInput{10});
s2 = str2num(userInput{11});
nrN = str2num(userInput{12});
n = str2num(userInput{13});
sname = userInput{14};

x=(userDensityMin:1:userDensityMax)';
stdx=std(x);
meanx=mean(x);

x2=(userFyMin:1:userFyMax)';
stdx2=std(x2);
meanx2=mean(x2);

fycdf= cdf('normal',x2,mean(x2),std(x2));
fypdf= pdf('normal',x2,mean(x2),std(x2));

p1= cdf('normal',x,mean(x),std(x));
p2= pdf('normal',x,mean(x),std(x));

fo_ = fitoptions('method','LinearLeastSquares','Normalize','on');
fycdffit = fittype('poly5');
f2 = fit(x2,fycdf,fycdffit,fo_);
```

```
pvec_fy=coeffvalues(f2);

fo_ = fitoptions('method','LinearLeastSquares','Normalize','on');
dens_cdffit = fittype('poly5');
f3 = fit(x,p1,dens_cdffit,fo_);

pvec_density=coeffvalues(f3);
%%



%  figure(5)
%  grid on
%  plot(f2,x2,fycdf);
%
%  figure(6)
%  grid on
%  plot(f3,x,p1);
%
%  figure(10)
%  plot(x2,fypdf,'b.');
%  grid on
%
%  figure(11)
%  plot(x,p2,'b.');
%  grid on

%((z-meanx2)/stdx2)
syms p1 p2 p3 p4 p5 p6 z1 z rnd1;
fyDynamicCurveFit=solve('p1*z1^5 + p2*z1^4 + p3*z1^3 + p4*z1^2 + p5*z1 +
p6=rnd1');
rnd1=1;
%fyEqSolution=solve(pvec_fy(1)*((z-meanx2)/stdx2)^5 + pvec_fy(2)*((z-
meanx2)/stdx2)^4 + pvec_fy(3)*((z-meanx2)/stdx2)^3 + pvec_fy(4)*((z-
meanx2)/stdx2)^2 + pvec_fy(5)*((z-meanx2)/stdx2) - rnd1 + pvec_fy(6), z)

%((w-meanx)/stdx)
syms q1 q2 q3 q4 q5 q6 w1 w rnd2;
DensityDynamicCurveFit=solve('q1*w1^5 + q2*w1^4 + q3*w1^3 + q4*w1^2 + q5*w1
+ q6=rnd2');
rnd2=1;
%DensityEqSolution=solve(pvec_density(1)*((w-meanx)/stdx)^5 +
pvec_density(2)*((w-meanx)/stdx)^4 + pvec_density(3)*((w-meanx)/stdx)^3 +
pvec_density(4)*((w-meanx)/stdx)^2 + pvec_density(5)*((w-meanx)/stdx) -
rnd2 + pvec_density(6), w)

%%



shinAkuma=input('Press any key to start simulation...');
tic

R=zeros(n,1);
FM=zeros(n,1);
F1=zeros(n,1);
F2=zeros(n,1);
F3=zeros(n,1);
density=zeros(n,1);
FH=zeros(n,1);
```

```
Move=zeros(n,1);
FY=zeros(n,1);
MPL=zeros(n,1);
disp('Calculating...')
rthick=zeros(3,1);
rthin=zeros(2,1);
FMThick=zeros(n,1);
FMThin=zeros(n,1);
FM1Thick=zeros(n,1);
FM2Thick=zeros(n,1);
FM3Thick=zeros(n,1);
FM1Thin=zeros(n,1);
FM2Thin=zeros(n,1);
%%

for i=1:1:n
    rnd1=rand(1,1);
    rnd2=rand(1,1);


    fyEqSolution=solve(pvec_fy(1)*((z-meanx2)/stdx2)^5 + pvec_fy(2)*((z-
meanx2)/stdx2)^4 + pvec_fy(3)*((z-meanx2)/stdx2)^3 + pvec_fy(4)*((z-
meanx2)/stdx2)^2 + pvec_fy(5)*((z-meanx2)/stdx2) - rnd1 + pvec_fy(6), z);
    DensityEqSolution=solve(pvec_density(1)*((w-meanx)/stdx)^5 +
pvec_density(2)*((w-meanx)/stdx)^4 + pvec_density(3)*((w-meanx)/stdx)^3 +
pvec_density(4)*((w-meanx)/stdx)^2 + pvec_density(5)*((w-meanx)/stdx) -
rnd2 + pvec_density(6), w);


    pickedDensity=double(DensityEqSolution(1));
    pickedFy=double(fyEqSolution(1));

    %Embedment str and plastic moment capactiy
    fh=0.082* pickedDensity*d^-0.3;
    Mpl=(pickedFy*d^3)/6;

    %Calculating resistance with fh and Mpl, Johanssen theory, output in Kn
    r=zeros(3,1);
    fm=[0 0 0]';
    FMT=[0 0 0]';
    FMth=[0 0]';
    if plate>=d
    %Thick plate
    r(1)= fh*d*t1/1000;
    r(2)= (fh*d*t1)*((2+(4*Mpl/(fh*d*t1^2)))^(1/2)-1)/1000;
    r(3)=2*sqrt(Mpl*fh*d)/1000;
    rtemp=r;
    rsort=sort(rtemp);
    R(i)=rsort(1);
    %disp('thick')
    end
    if plate<=0.5*d
    %thin plates
    r(1)= 0.4*fh*d*t1/1000;
    r(2)=sqrt(2*Mpl*fh*d)/1000;
    r(3)=9999999999;
    rtemp=r;
    rsort=sort(rtemp);
    R(i)=rsort(1);
    %disp('thin')
```

```
end


if plate>0.5*d && plate<d
%Interpolation tjock tunn plåt
rthick(1)= fh*d*t1/1000;
rthick(2)= (fh*d*t1)*((2+(4*Mpl/(fh*d*t1^2)))^(1/2)-1)/1000;
rthick(3)=2*sqrt(Mpl*fh*d)/1000;
rthickmin=sort(rthick);

rthin(1)= 0.4*fh*d*t1/1000;
rthin(2)=sqrt(2*Mpl*fh*d)/1000;
rthinmin=sort(rthin);
FM1Thick(i)=rthick(1);
FM2Thick(i)=rthick(2);
FM3Thick(i)=rthick(3);

FM1Thin(i)=rthin(1);
FM2Thin(i)=rthin(2);
R(i)=rthinmin(1)+((rthickmin(1)-rthinmin(1))/(1-0.5))*((plate/d)-0.5);
%disp('interpol')

 for k=1:1:3
    for j=1:1:3
        if(rthickmin(k)==rthick(j))
            FMT(k)=j;
        end
    end
 end
 for k=1:1:2
    for j=1:1:2
        if(rthinmin(k)==rthin(j))
            FMth(k)=j;
        end
    end
 end

end

rtemp=r;
rsort=sort(rtemp);


if(plate<=0.5*d || plate>=d)
for k=1:1:3
    for j=1:1:3
        if(rsort(k)==r(j))
            fm(k)=j;
        end
    end
end

FM(i)=fm(1);
F1(i)=r(1);
F2(i)=r(2);
F3(i)=r(3);
density(i)=pickedDensity;
FH(i)=fh;
FY(i)=pickedFy;
```

```
    MPL(i)=Mpl;
    %disp('thinthick2')
    end

    if(plate>0.5*d && plate<d)
    FMThick(i)=FMT(1);
    FMThin(i)=FMth(1);
    density(i)=pickedDensity;
    FH(i)=fh;
    FY(i)=pickedFy;
    MPL(i)=Mpl;
    %disp('interpol2')
    end

disp((i/n)*100)

end
%%





%%
%%

% StringPath='I:\Alex\SER-(';
StringPath = strcat('D:\XJOUT\SER-',sname,'-(');
str0x=') Density(';
str00=int2str(userDensityMin);
str01=int2str(userDensityMax);
str11= strcat(str00,'-' ,str01,')');
str2x=' YieldStr(';
str22=int2str(userFyMin);
str23=int2str(userFyMax);
str33= strcat(str22,'-', str23, ')');
str1=' n';
str2= int2str(d);
str3=' p';
str4= int2str(t1);
str5=' t';
str6= int2str(plate);
Fname=datestr(now,'mmmm dd, yyyy HH,MM,SS');
SF = strcat(StringPath, Fname,str0x,str11,str2x, str33, str1, str2, str3,
str4, str5, str6);
StringA={'Resistance','Failure Mode','Density','Fh','Fy','Mpl','','FM
Thick','FM Thin','','FM 1','FM 2','FM 3','','FM 1 THICK','FM 2 THICK','FM 3
THICK','FM 1 THIN','FM 2 THIN'};
xlswrite(SF, StringA,1,'A1')
xlswrite(SF, R,1,'A2')
xlswrite(SF, FM,1,'B2')
xlswrite(SF, density,1,'C2')
xlswrite(SF, FH,1,'D2')
xlswrite(SF, FY,1,'E2')
xlswrite(SF, MPL,1,'F2')
xlswrite(SF, FMThick,1,'H2')
xlswrite(SF, FMThin,1,'I2')
xlswrite(SF, FM1Thick,1,'O2')
xlswrite(SF, FM2Thick,1,'P2')
xlswrite(SF, FM3Thick,1,'Q2')
xlswrite(SF, FM1Thin,1,'R2')
```

```
xlswrite(SF, FM2Thin,1,'S2')

xlswrite(SF, F1,1,'K2')
xlswrite(SF, F2,1,'L2')
xlswrite(SF, F3,1,'M2')
%%

disp('Done!')
disp(' ')
toc
disp(' ')
steptime=toc;

res1= cdf('normal',R,mean(R),std(R));
res2= pdf('normal',R,mean(R),std(R));




%%
% figure(2)
% grid on
% disp('Plotting...')
% if(plate<=0.5*d || plate>=d)
% %For thin or thick plate plot
% for i=1:1:n
%     if(FM(i)==1)
%        figure(2)
%        hold on
%        plot(R(i),res2(i),'o','LineWidth',2,...
%                 'MarkerEdgeColor','k',...
%                 'MarkerFaceColor','b',...
%                 'MarkerSize',5);
%     end
%     if(FM(i)==2)
%        figure(2)
%        hold on
%        plot(R(i),res2(i),'o','LineWidth',2,...
%                 'MarkerEdgeColor','k',...
%                 'MarkerFaceColor','r',...
%                 'MarkerSize',5);
%     end
%     if(FM(i)==3)
%        figure(2)
%        hold on
%        plot(R(i),res2(i),'o','LineWidth',2,...
%                 'MarkerEdgeColor','k',...
%                 'MarkerFaceColor','g',...
%                 'MarkerSize',5);
%     end
%
%
% end
% end
%
% if(plate>0.5*d && plate<d)
%     for i=1:1:n
%      figure(2)
%      hold on
%      grid on
```

```
%       plot(R(i),res2(i),'r+')
%      end
% end

%}
%{

for(i=1:1:n)
     if(FM(i)==1)
        figure(2)
        hold on
        plot(R(i),res2(i),'bo')
     end
     if(FM(i)==2)
        figure(2)
        hold on
        plot(R(i),res2(i),'ro')
     end
     if(FM(i)==3)
        figure(2)
        hold on
        plot(R(i),res2(i),'go')
      % disp((i/n)*100)
     end

 end
%}

%

% figure(2)
% plot(R,res1,'+')
%

% figure(3)
% plot(R,res2,'+')


disp('Done')
disp(' ')
stoptime=toc;
toc
disp(' ')
disp('Runtime/Simulation (sec) Calculation :')
disp(steptime/n)
disp('Runtime/Simulation (sec) Calculation+Plot:')
disp(stoptime/n)

figure(4)
grid on
plot(f1,R,res1)
grid on
Rsortt=sort(R);
xlabel('Resistance');
ylabel('');
title(sname);
```

Appendix C
Nail bending test results

Length	*Nail ID*	F_y [N]	M_y [Nmm]	f_y [MPa]
40 mm	***1***	1479	9612	901
	2	1432	9307	872
	3	1423	9252	867
	4	1400	9099	853
	5	1454	9448	886
	6	1430	9296	871
	7	1541	10016	939
	8	1475	9590	899
	9	1425	9263	868
	10	1464	9514	892
60 mm	***1***	793	8925	837
	2	864	9718	911
	3	791	8903	835
	4	854	9603	900
	5	813	9146	857
	6	851	9573	897
	7	852	9586	899
	8	818	9198	862
	9	829	9324	874
	10	750	8443	792

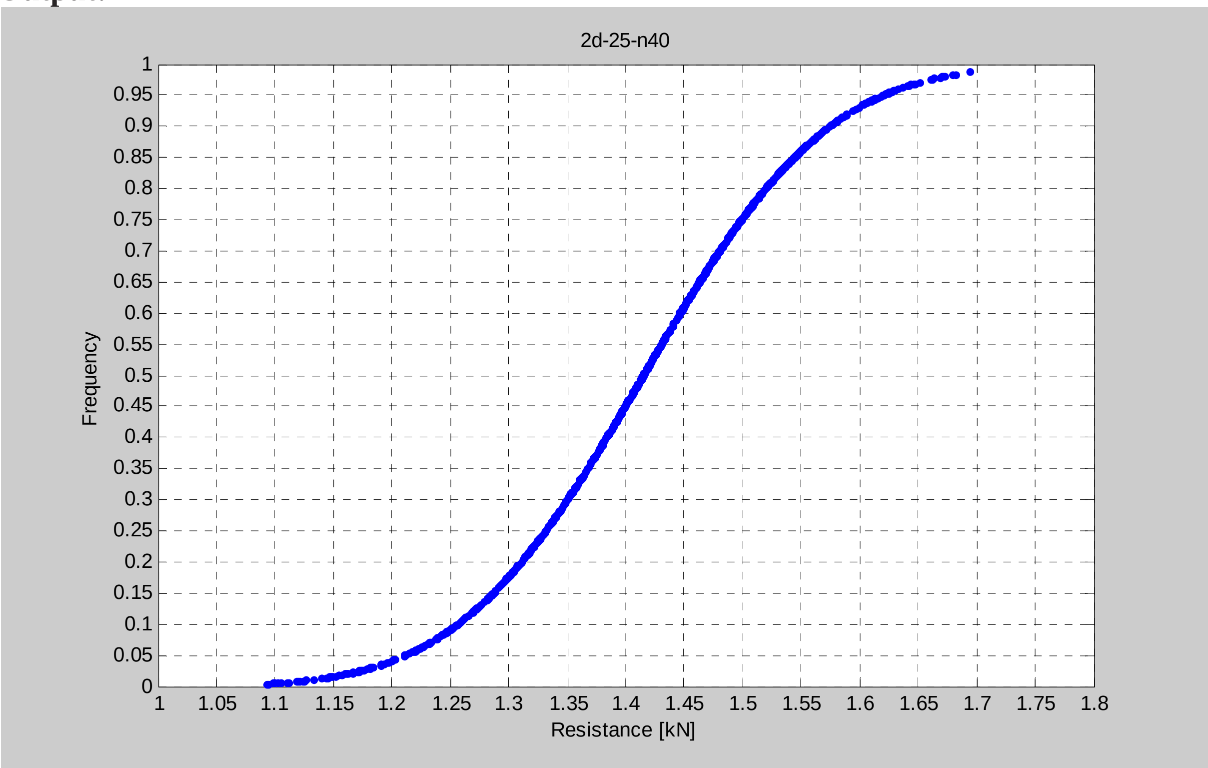
Mean	**9341**	**876**
Characteristic	8752	832

Appendix D
Simulation results

Simulation results 2d-25-n40:

Input:
Density range: 349-536 kg/m^3
Yield strength range: 792-939 Mpa
Nail penetration length: 35mm
Plate thickness: 2.5mm
Nail diameter: 4mm
Nr of sims: 2000

Output:



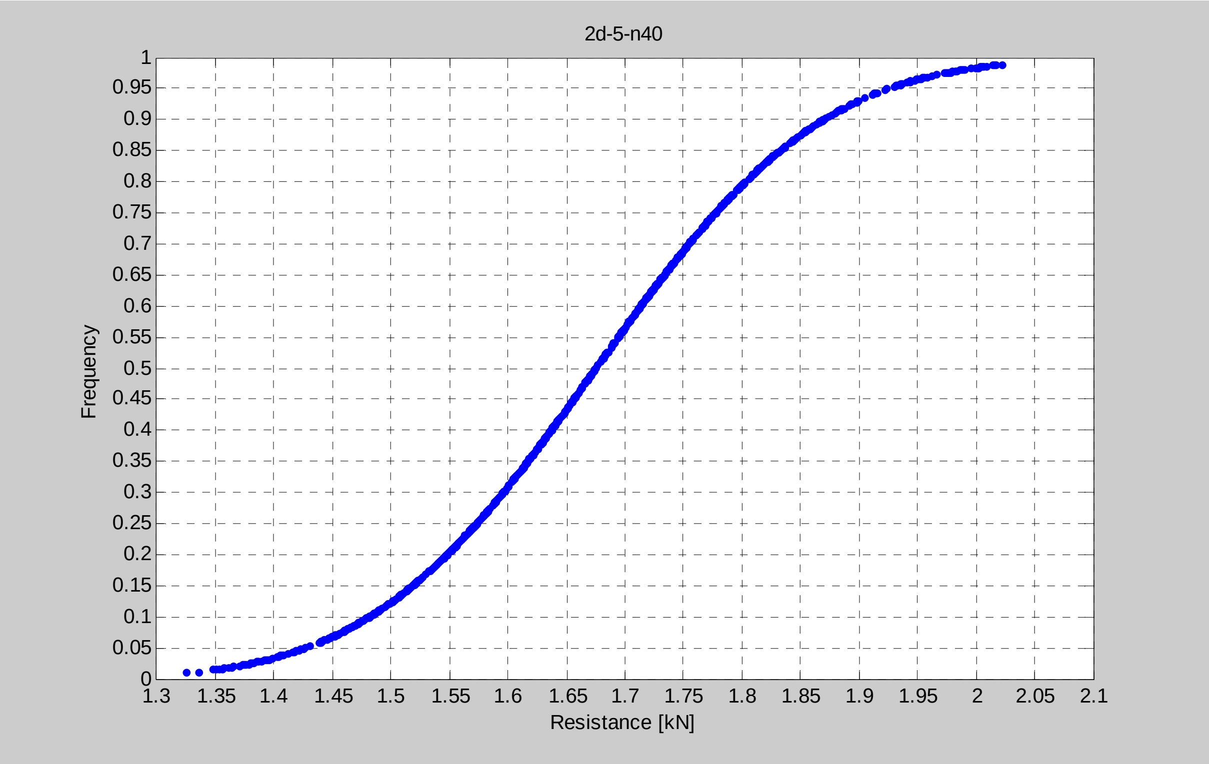
Failure mode: 2 both thick and thin

Interpolation formulation:
Mean value: 1,42 kN
Characteristic value: 1,18 kN
Thick plate formulation:
Mean value: 1,75 kN
Characteristic value: 1,48 kN
Thin plate formulation:
Mean Value: 1,33 kN
Characteristic value: 1,2 kN

Simulation results 2d-5-n40:

Input:
Density range: 349-536 kg/m^3
Yield strength range: 792-939 Mpa
Nail penetration length: 32.5mm
Plate thickness: 5mm
Nail diameter: 4mm
Nr of sims: 2000

Output:



Failure mode: 2

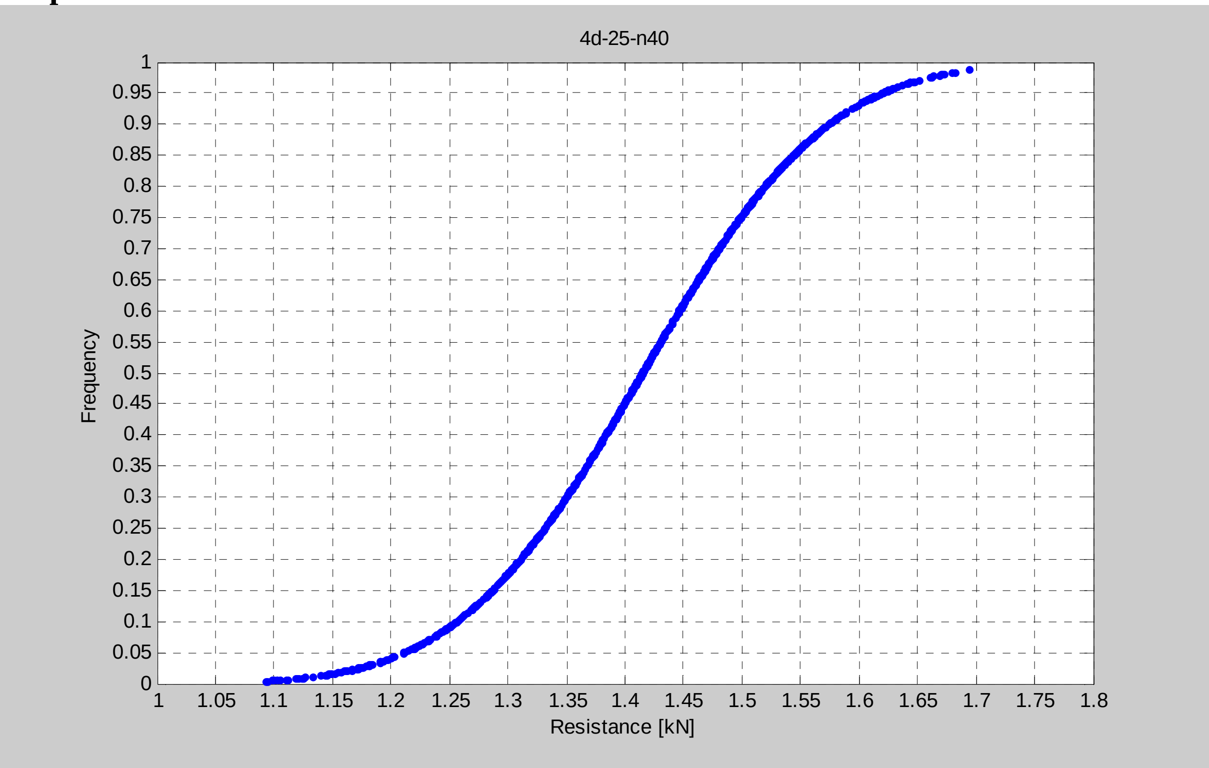
Thick plate formulation:
Mean value: 1,67 kN
Characteristic value: 1,41 kN

Simulation results 4d-2.5-n40:

Because the simulation model simulates a one nail connection the results will be the same as the 2d-2.5-n40 series because they have the same steel plate and the same nail length.
Input:

Density range: 349-536 kg/m^3
Yield strength range: 792-939 Mpa
Nail penetration length: 35mm
Plate thickness: 2.5mm
Nail diameter: 4mm
Nr of sims: 2000

Output:



Failure mode: 2 both thick and thin

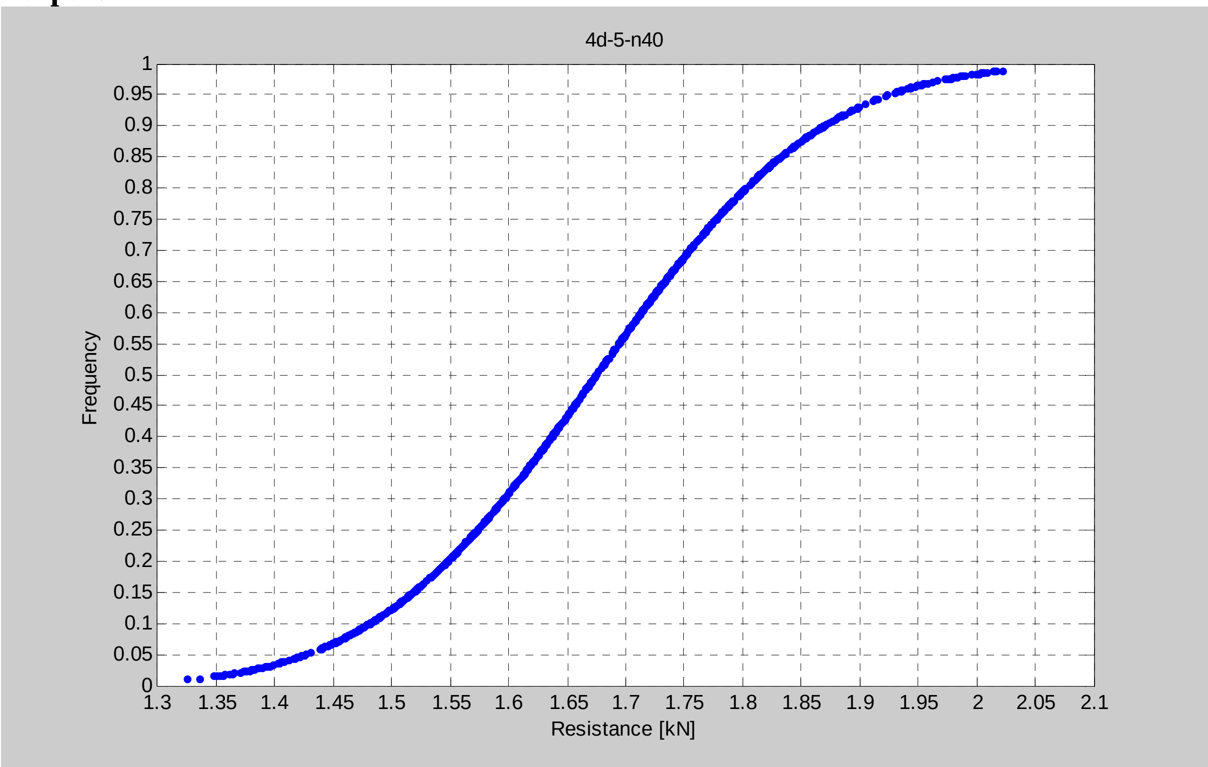
Interpolation formulation:
Mean value: 1,42 kN
Characteristic value: 1,18 kN
Thick plate formulation:
Mean value: 1,75 kN
Characteristic value: 1,48 kN
Thin plate formulation:
Mean Value: 1,33 kN
Characteristic value: 1,2 kN

Simulation results 4d-5-n40:

Because the simulation model simulates a one nail connection the results will be the same as the 2d-5-n40 series because they have the same steel plate and the same nail length.
Input:

Density range: 349-536 kg/m^3
Yield strength range: 792-939 Mpa
Nail penetration length: 32.5mm
Plate thickness: 5mm
Nail diameter: 4mm
Nr of sims: 2000

Output:



Failure mode: 2

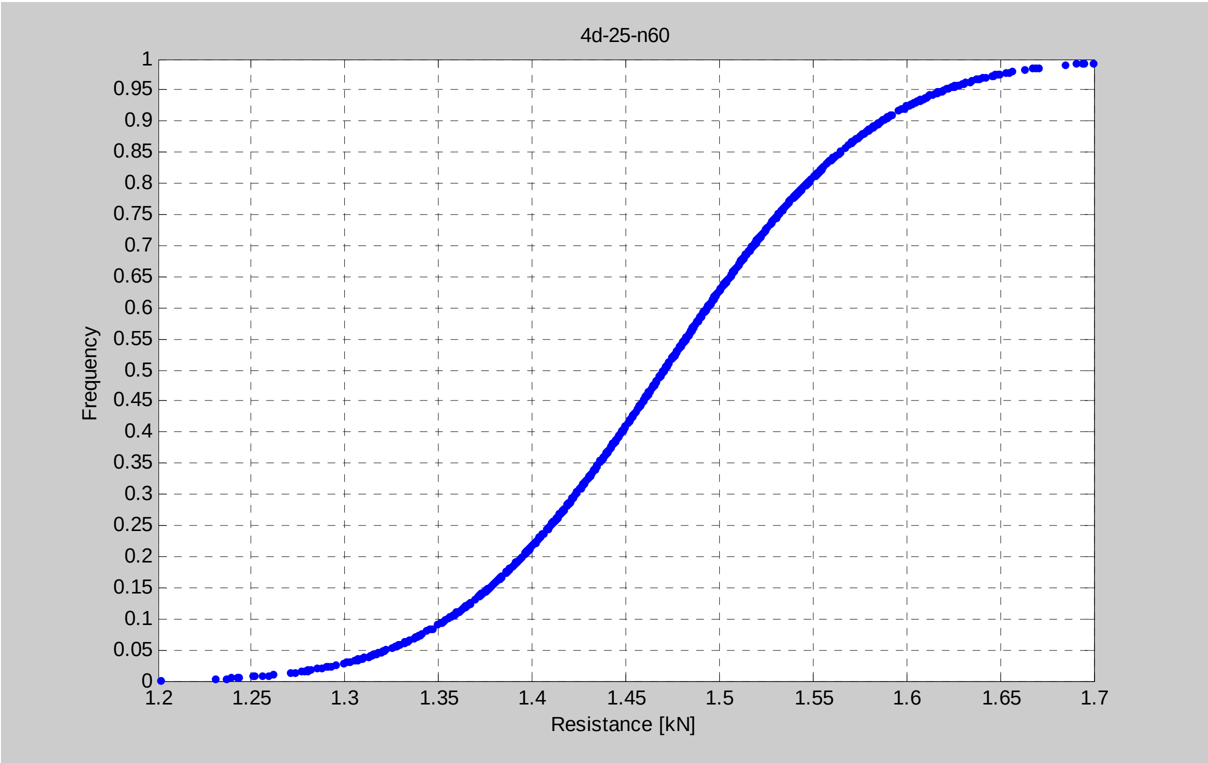
Thick plate formulation:
Mean value: 1,67 kN
Characteristic value: 1,41 kN

Simulation results 4d-2.5-n60:

Input:

Density range: 349-536 kg/m^3
Yield strength range: 792-939 Mpa
Nail penetration length: 55mm
Plate thickness: 2.5mm
Nail diameter: 4mm
Nr of sims: 2000

Output:



Failure mode: 3 for thick and 2 for thin formulation

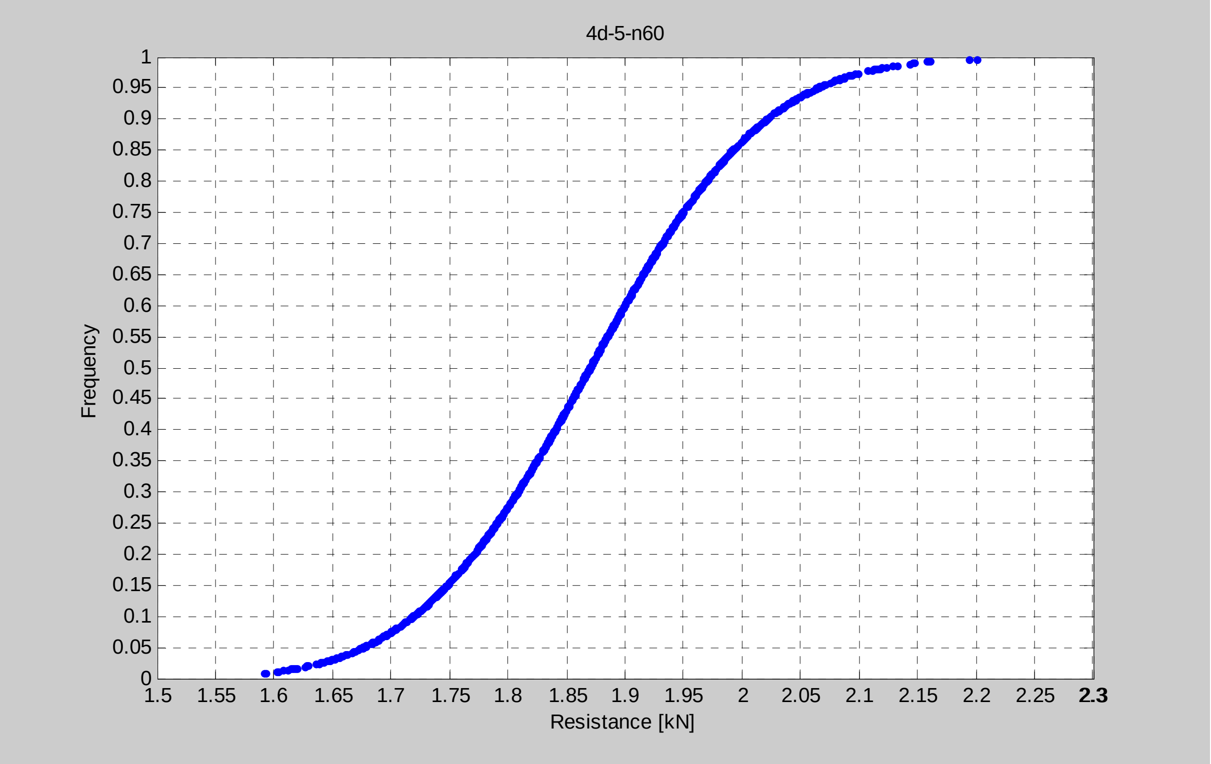
Interpolation formulation Eurocode:
Mean value: 1,46 kN
Characteristic value: 1,3 kN
Thick plate formulation:
Mean value: 1,85 kN
Characteristic value: 1,66 kN
Thin plate formulation:
Mean Value: 1,35 kN
Characteristic value: 1,17 kN

Simulation results 4d-5-n60:

Input:

Density range: 349-536 kg/m^3
Yield strength range: 792-939 Mpa
Nail penetration length: 52.5mm
Plate thickness: 5mm
Nail diameter: 4mm
Nr of sims: 2000

Output:



Failure mode: 3

Thick plate formulation:
Mean value: 1,88 kN
Characteristic value: 1,67 kN

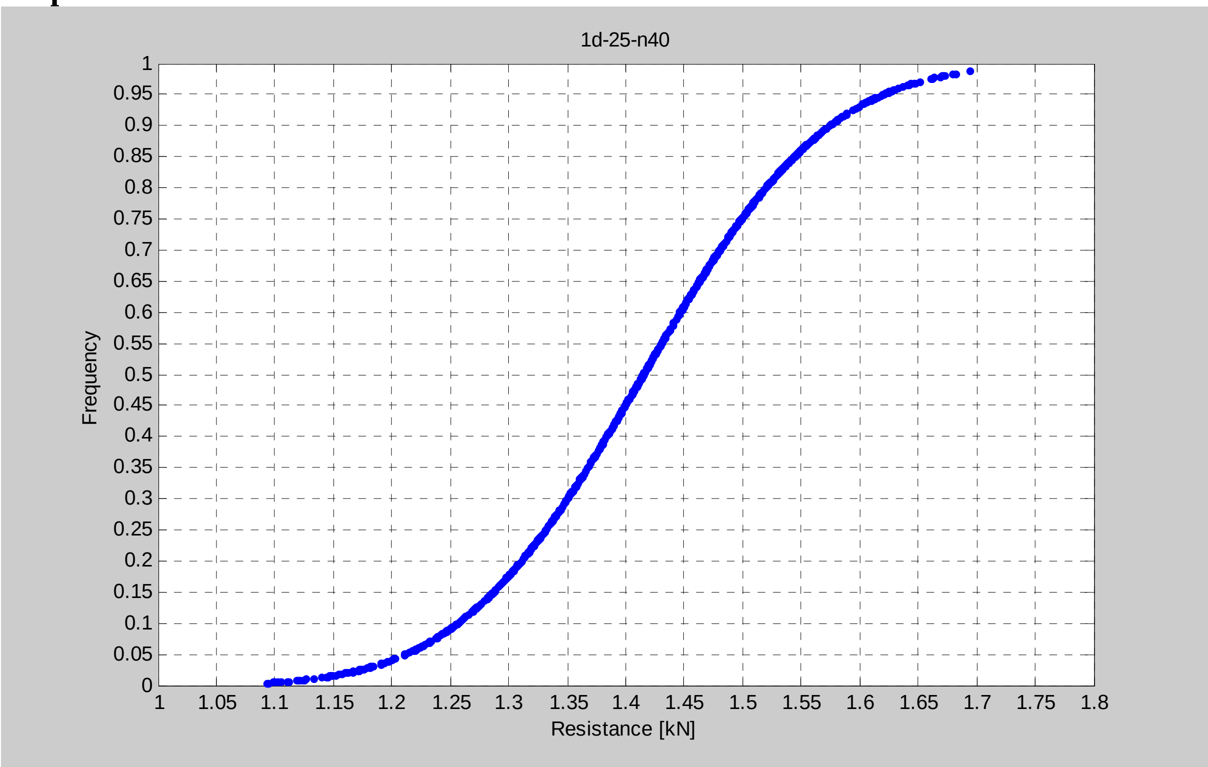
Simulation results 1d-2.5-n40:

Because the simulation model simulates a one nail connection the results will be the same as the 2d-2.5-n40 series because they have the same steel plate and the same nail length.

Input:

Density range: 349-536 kg/m^3
Yield strength range: 792-939 Mpa
Nail penetration length: 35mm
Plate thickness: 2.5mm
Nail diameter: 4mm
Nr of sims: 2000

Output:



Failure mode: 2 both thick and thin

Interpolation formulation:
Mean value: 1,42 kN
Characteristic value: 1,18 kN
Thick plate formulation:
Mean value: 1,75 kN
Characteristic value: 1,48 kN
Thin plate formulation:
Mean Value: 1,33 kN
Characteristic value: 1,2 kN

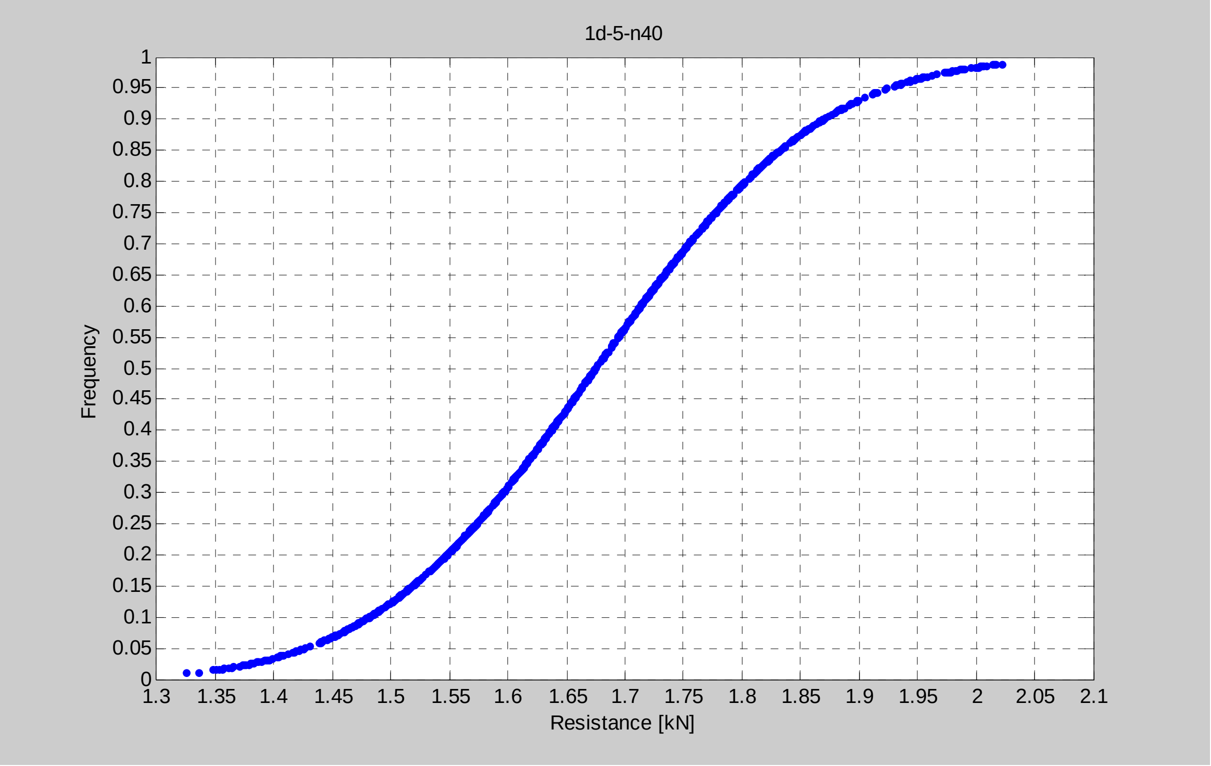
Simulation results 1d-5-n40:

Because the simulation model simulates a one nail connection the results will be the same as the 2d-5-n40 series because they have the same steel plate and the same nail length.

Input:

Density range: 349-536 kg/m^3
Yield strength range: 792-939 Mpa
Nail penetration length: 32.5mm
Plate thickness: 5mm
Nail diameter: 4mm
Nr of sims: 2000

Output:



Failure mode: 2

Thick plate formulation:
Mean value: 1,67 kN
Characteristic value: 1,41 kN

Appendix E

Standard template for test performed

SERIES:

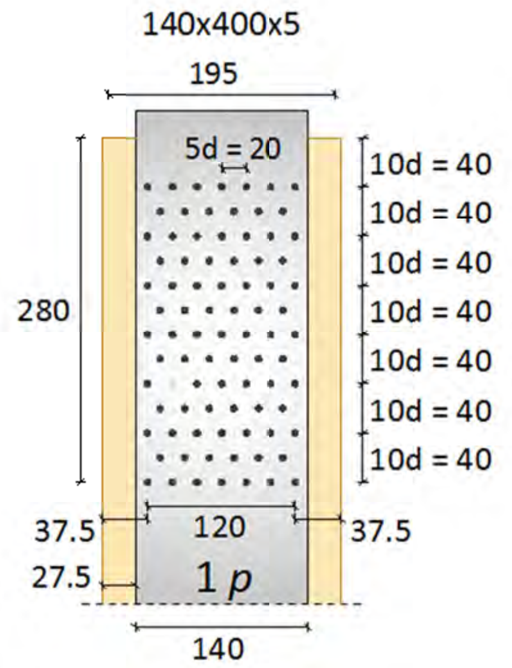
ID:

PRE-TEST

Measured moisture (%): [ ] [ ] [ ]
Measured weight [kg]:
Size:
Measured volume [m^3]:
Density [kg/ m^3]:

AFTER-TEST

Measured Deformation [mm]: TOP: BOTTOM:
Brittle or ductile failure? :
Failure mode:
Ultimate load [kN]:



Example of pattern that was tested.

Observations / Comments:

PLUG SHEAR? [YES / NO]

Total Plug weight [kg]:

Steel plate(s) weight + nails weight [kg]:

Plug weight [kg]:

Measured length [m]:

Measured width [m]:

	Plug W [kg]			
	Density [kg/m3]			
	Volume [m3]			
	Measured length [m]			
	Measured width [m]			
	Calculated plug depth [m]			
	Bottom shear area [m^2]			
	Side shear area [m^2]			
	Tension area [m^2]			
	Total area			