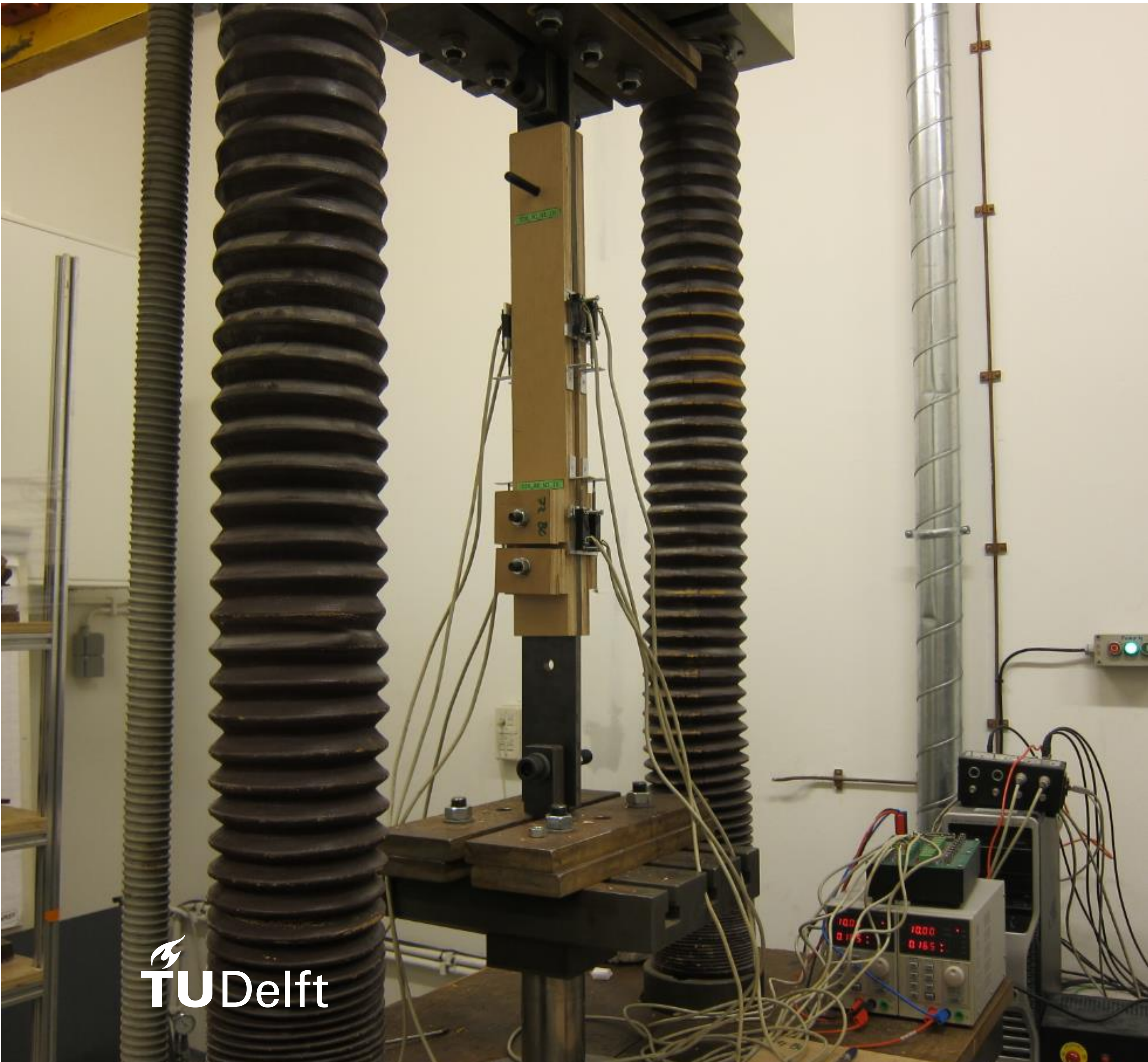
Experimental analysis of connections in LVL-Q beech timber for application in moment resisting connections



By

L. van Rijssel

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TU Delft

Supervisor:	Ir. P.A. de Vries	TU Delft
	Dr. Ir. G.J.P. Ravenshorst	TU Delft
Thesis committee:	Prof. dr. ir. J.W.G. van de Kuilen	TU Delft
	Ir. J.M. Houben	TU Delft
	Ir. P.A. de Vries	TU Delft
	Dr. Ir. G.J.P. Ravenshorst	TU Delft

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1 Preface and acknowledgements

Before you lies my master thesis report for my study in Civil Engineering(Structural engineering). Ever since I continued my study from the University of applied Science(Hogeschool van Amsterdam), I was interested in doing experimental testing and this eventually led to this this master thesis on connections in LVL-Q timber. The research was done at the StevinLab at Delft University of technology.

With this thesis I'd like to conclude my study and I'd like to take this moment to show my thanks and appreciation to anyone who aided me during this master thesis.

In particular I would like to give my thanks and appreciation to the company Pollmeier for supplying beech LVL-Q timber for this research without this, the tests and this master thesis wouldn't have been possible. Also I'd like to thank all the lab and workshop personnel Ruben, John, Kevin, Fred and the many more who helped me in either preparing the test specimen, or preparations for the tests.

My special thanks goes out to my supervisors Geert Ravenshorst and Peter de Vries for their guidance and assistance until the very end to finish this master thesis. The last weeks have been the most intensive and I highly appreciated the extra time you spent on me, discussing, giving extra feedback and remarks to finalize my work. In addition to this I'd like to thank Lambert Houben and Jan-Willem van de Kuilen for giving their valuable feedback, guidance and opinions on my master thesis.

And lastly I'd like to thank my family and friends for their patience and support during my studies.

I hope you enjoy reading this master thesis report,

2 Abstract

In current design practise timber moment resisting connections are always designed in Failure mode II/III, to ensure ductility within the connection. This design practice however is not the most efficient for creating an high capacity connection. In the literature study of this research was found that LVL-Q had a very high embedment deformation much larger than usual timber products. This formed the idea for creating a moment resisting connection which fails in Failure mode I instead of II or III. Improving the efficiency of timber connections and leading to a higher strength connection

Due to the lack of information on the behavior of LVL-Q in all directions which is generally required for moment resisting connection, tensile tests have been done to determine the behavior of LVL-Q in different directions. This to analyse the embedment strength and ductility of LVL-Q. Embedment strength found in the tests reached a strength of 86N/mm^2 to 102N/mm^2 and large displacements of up to 15mm were reached.

During experiments was noted that when clamped together(which is usual practice with a nut and a bolt), the embedment strength increases in LVL-Q. This is due to the high deformation capacity of LVL-Q. During deformation a lot of material is pushed outwards, when prevented a densification occurs behind the dowel increasing the embedment strength. A Strength up to 130N/mm^2 was observed.

The idea of a moment resisting connections looks promising as the design calculation of a moment resisting connection, led to a moment capacity(26 % stronger) than the beam it was connected to. Given the current dimensions(paragraph 10) this is a bit impractical, but can certainly improve by creating a connection with multiple shear planes failing in mode I. The increase in strength however allows other failure modes such as shear failure in the middle of the joint to be governing this however requires additional research.

3 Introduction

In timber construction hinged joints are often preferred over moment resisting connections. This is due to the unfavorable properties of timber when it comes to the design of mechanical connections. Timber which has a strong longitudinal strength but a perpendicular and tangential strength is the main reason for this.

Timber in the last years has become more popular in structural engineering due to its environmental benefits over the other options such as concrete and steel. As it is renewable and CO_2 neutral in a lot of the cases. With this increasing trend companies are investing in more timber technologies. Laminated veneer Lumber(LVL) is one of this products. The concept of the product in itself is not new and is similar to plywood. The difference is the alignment of the veneers. While plywood has the veneers evenly distributed in both directions, LVL has the veneers all in one direction or just a small percentage. The benefits this is a better homogeneity and thus a higher strength.

The focus of this master thesis is on the LVL with a percentage of cross layers in one direction with the focus on dowelled moment resisting connection. Currently LVL with cross layers(LVL-Q) is a material in between sawn timber or plywood. However it is neither of these two, however no different design rules exist for this type of material. This limits the possible uses of this material.

The goal of this master thesis is to find out what the behavior is of LVL with cross layers and whether this material is an effective material in combination with moment resisting connections. Unlike plywood LVL with cross layers(LVL-Q) has still a high strength in longitudinal direction while having a significantly larger perpendicular strength unlike regular sawn timber. This is likely to benefit moment resisting connections which have splitting as a common brittle failure.

The two species in Europe used for LVL are either spruce or beech, with spruce being the more commonly used. For this research beech will be used as its ductility and strength is better than spruce which is beneficial in moment resisting connections.

3.1 *Laminated veneer Lumber*

Laminated veneer Lumber is a sustainable material that can be made from a range of different timber species. In Europe this is mainly the softwood spruce or the hardwood beech. The production process is shown Figure 1. During “adhesive application and laying of veneers” type of product is defined. This step defines whether LVL-S(All parallel veneers), LVL-Q(Partial cross lamination) or plywood(evenly distributed cross lamination) is produced.

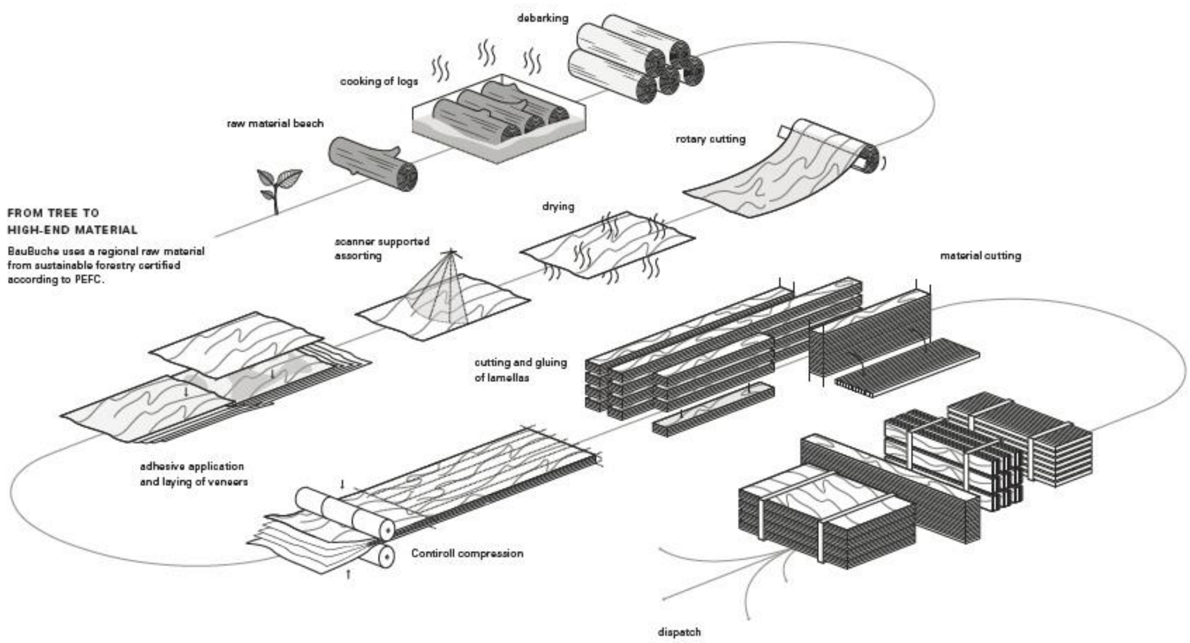


Figure 1 Production process off LVL source: Baubuche-Pollmeier

The production process of LVL removes some of the defects that are usually found in timber:

- Knots and imperfections don’t penetrate the full cross section anymore because the veneers are rearranged and the imperfections do not align with each other.
- The rotary peeling process makes all veneers align in one direction, reducing/negating the effects of growth rings

Due to this process the mechanical properties are improved. The process is further shown on the next page with pictures of the production process of Baubuche beech. The timber used for this research.

Figure 2 Beech logs used Baubuche LVL. [7]

Figure 3 Rotary peeling of beech logs[7]

Figure 4 Grading of the veneers[7]

Figure 5 Spray glue on the veneers[7]

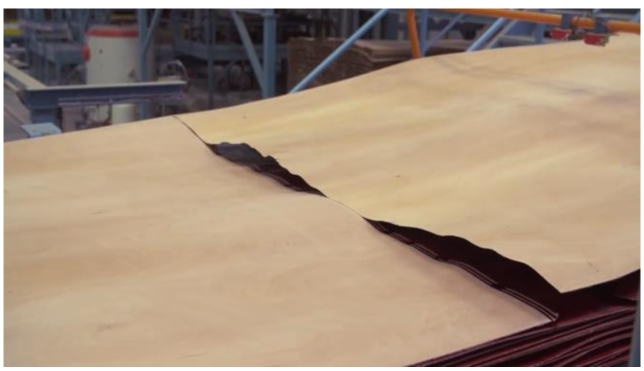


Figure 6 laying of the veneers[7]

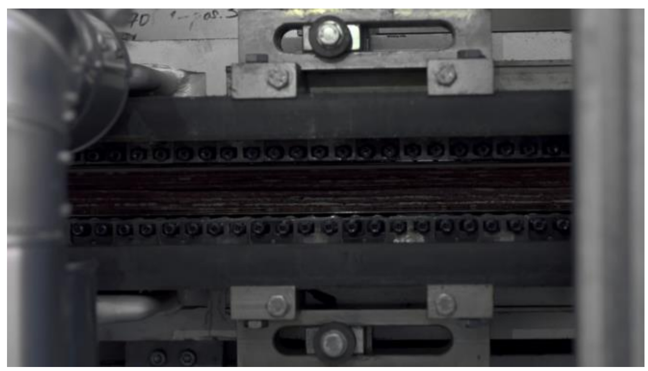


Figure 7 Pressing of the veneers[7]

Figure 8 Final product(Baubuche-S)[7]

4 Research

The interest in the use of LVL-Q came from the following research question:

Is it possible to design a moment resisting connection in LVL-Q timber which has a higher moment capacity than the moment capacity of the timber its connected to?

In past research for timber multiple researches have tried to design various type of connections to make a strong moment resisting connection in timber. This is however difficult and some research indeed succeeded in making such connection this however also came with significantly higher costs that this is still not commonly used in timber structures. The main problem is to overcome the weak perpendicular properties of timber. This research tries to make use of commonly used connection in combination with LVL-Q beech.

The use of LVL-Q does mean that the bending strength of the timber beams will be lower when compared with LVL-S but about equal when compared to beech timber.

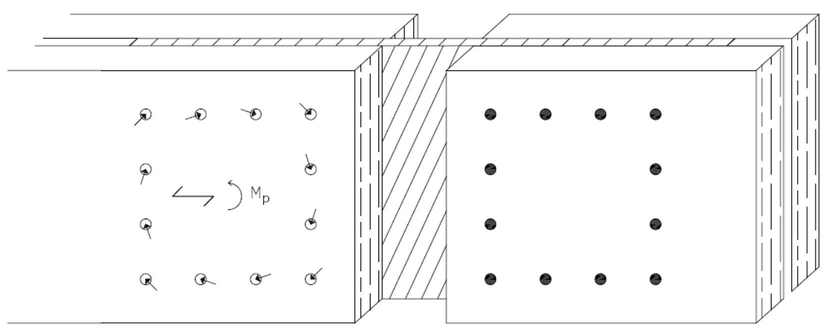


Figure 9 Moment resisting connection

The current properties of LVL-Q are still underdeveloped and the determination of properties such as embedment strength are still in research. This research focusses on the determination of dowel behavior of dowels in moment resisting connections.

4.1 Research questions

To determine the capacity of a moment resisting connection it is required to investigate the behavior of dowels in LVL-Q. This to analyze what is the load carrying capacity of individual dowels and how do these relate to strength and stiffness.

- ***What is the behavior of dowelled connections in LVL-Q and how does this change in different loading angles to the grain?***

In determining the position and preventing brittle failures such as splitting the dowels have to be placed at appropriate distances. Therefor the dowels positioning is analyzed in which splitting or any other brittle failures occur. For this the distances as described by the timber code Eurocode 5 are used and is researched whether there is the possibility to reduce these distances compared to the current standard.

- ***Does splitting or any other brittle failures occur for end distances as given by the Eurocode 5 and can these be reduced?***

In the design of dowels applying multiple dowels in row leads to a reduced strength as one dowels starts to show brittle behavior or loss of strength before the other. Therefor the strength is reduced according to the number of dowels and the distance in between. With the expectation of LVL-Q showing more ductile behavior a more efficient strength can be achieved.

- ***What is the influence on the load carrying capacity of the dowels when multiple dowels are used.***

4.2 Master thesis

This master thesis research will start off with a literature study on dowelled connections connection timber. In this will be explained the theory behind these connections and other possible methods. Based on this literature study a research plan has been set up to determine the properties required to answer the research questions.

5 Theory and literature study

5.1 Embedment behavior timber

The embedment strength is the main parameter of the strength of dowels in timber. It's the base value for use in the Johansen equations used to calculate the strength of dowelled or nailed timber connections. This is shown in the figure below. This is the strength that is measured when the timber is "crushed" behind a dowel.

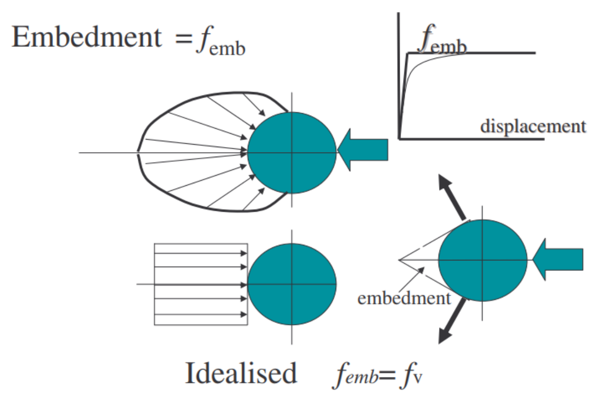


Figure 10 source[9] Leijten, simplified embedment strength in timber

This and the strength of the dowels are the main parameters used to determine the strength of timber connections in timber joints. The dowel determines it's strength by its resistance to bending.

In the figure below the test setup for embedment tests is shown. The standard method however varies per continent/country. Below the American standard left figure and European standard right figure. Test setups lead to slightly different results, however this is another discussion in itself.

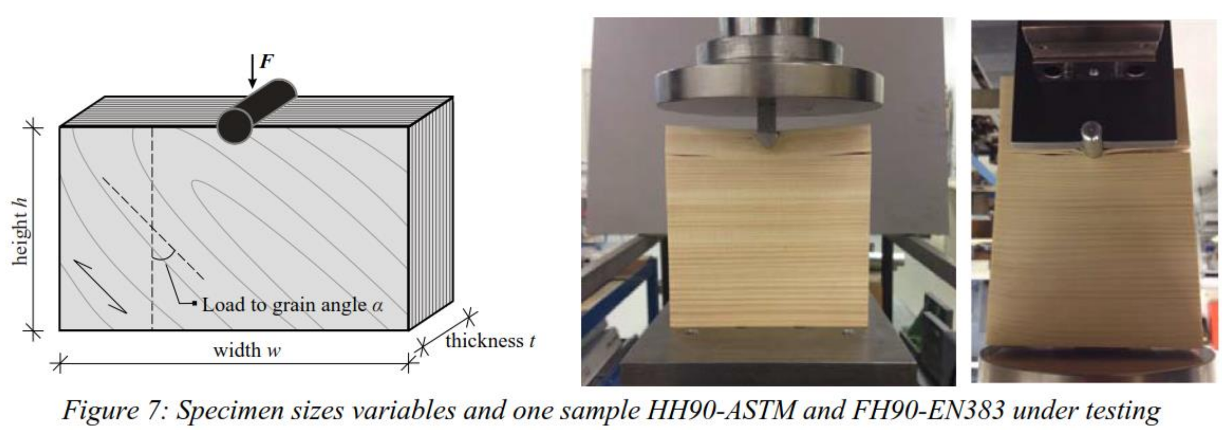


Figure 11 source[10] Test setup to determine embedmentstrength

Failure modes are referred by as failure mode I,II or III.

- With failure mode I being embedment failure in the timber.(dowel will remain straight)
- Failure mode II with 1 plastic hinge forming in the timber and the rest of the deformation from crushing of the timber(figure 10 in figure below).
- Failure mode III with 2(or more) plastic hinges forming in the timber. Allowing the dowel to deform indefinitely

Often is constructed in failure mode II/III as it's the best option to distribute forces in the timber aswell as allowing a structure to show deformation before failure. The strength in which failure occurs is determined by assuming a certain failure mode and calculating force(force P in this case) and calculate the shear force per shear plane. Calculating all possible failure mechanisms and taking the lowest one determines the strength of the connection.

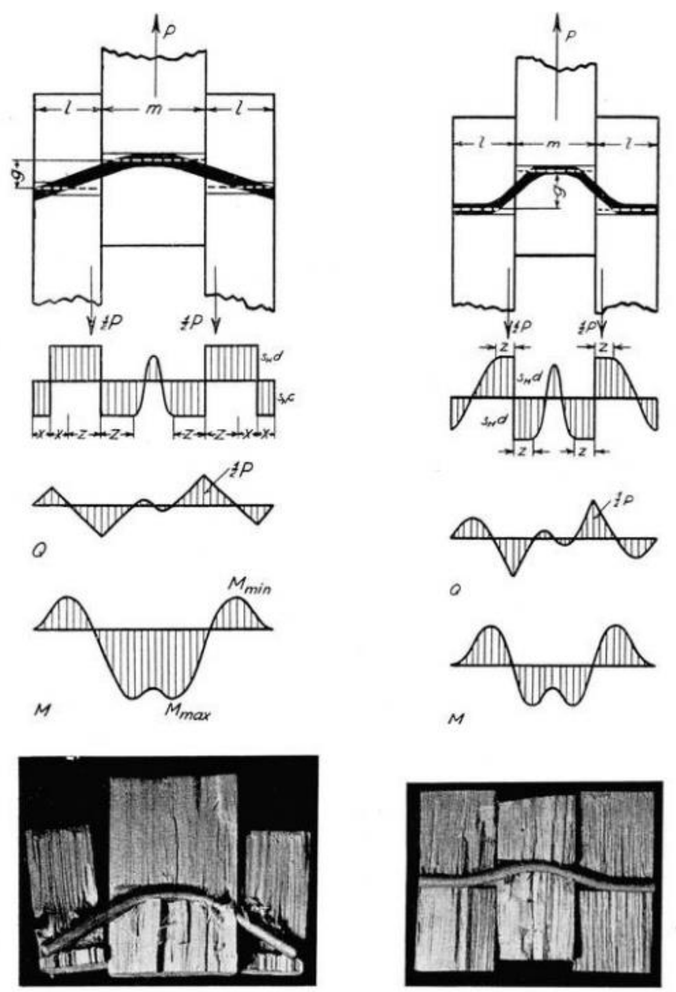


Fig. 10 Fig. 11

Figure 12 source [11]Failure mode II and Failure mode III in timber to timber double shear connections

The most often occurring failure modes for “standard” steel to timber connections are shown below.

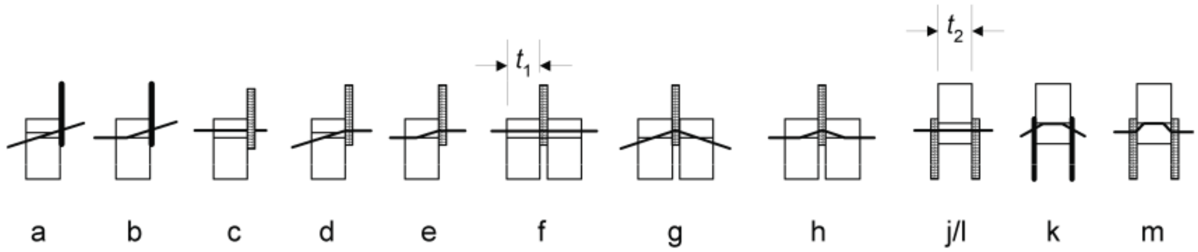


Figure 13 source[13] Failure modes in timber to steel connections EC5

The formula for each failure mode is derived separately by assuming the depicted failure modes. The formula given below are for timber-steel with a double shear plane which are used in the tensile tests of this thesis.

$$F_{\mathrm{v,Rk}} = \min \begin{cases} f_{\mathrm{h,1,k}} t_1 d & \text{(f)} \\ f_{\mathrm{h1,k}} t_1 d \left[\sqrt{2 + \dfrac{4 M_{y,\mathrm{Rk}}}{f_{\mathrm{h,1,k}} d t_1^2}} - 1 \right] + \dfrac{F_{\mathrm{ax,Rk}}}{4} & \text{(g)} \\ 2{,}3 \sqrt{M_{y,\mathrm{Rk}} f_{\mathrm{h,1,k}} d} + \dfrac{F_{\mathrm{ax,Rk}}}{4} & \text{(h)} \end{cases} \qquad (8.11)$$

Figure 14 source [13] Design equations timber-steel-timber connections

With :

$M_{y,Rk}$=Moment capacity of the dowel calculated by $M_{y,Rk}=0.3*f_u*d^{2.6}$
Note: $M_{y,Rk}$: is calculated using an empirical formula instead of the elastic/plastic bending moment capacity
d=dowel diameter
t_1=timber thickness
f_{h1k}=embedment strength in the direction of loading

The last term $F_{ax,Rk}$ is the contribution by rope effect. This is an axial force in the dowel(or screw) which contributes to the shear force when bending. This occurs only with bending as in this case there is a horizontal and vertical component, in which the vertical components contributes to the shear force per shear plane. This term is generally taken as 0, when it is implemented in the calculation the axial force has to be determined by experiments.

The embedment is calculated based on empirical formulas based on the density of wood. Higher density wood leads to higher strength. The formulas which are shown below, are formulas which were determined in the past and to this day are still used to determine its strength.

The determination of strength is parallel to the grain, while the strength for any other angle to the grain is based on the base strength parallel to the grain and is an empirical derivation. And can also be derived by experiments through:

$$k_{90} = \frac{f_{h;0;k}}{f_{h;90;k}}$$

Embedment strength in solid timber:

$$f_{\mathrm{h},\alpha,\mathrm{k}} = \frac{f_{\mathrm{h,0,k}}}{k_{90}\sin^2\alpha + \cos^2\alpha} \quad (8.31)$$

$$f_{\mathrm{h,0,k}} = 0{,}082(1 - 0{,}01d)\rho_{\mathrm{k}} \quad (8.32)$$

For plywood:

$$f_{\mathrm{h,k}} = 0{,}11(1 - 0{,}01d)\rho_{\mathrm{k}} \quad (8.36)$$

K_{90} factors for determination of strength in other directions.(other than parallel)

$$k_{90} = \begin{cases} 1{,}35 + 0{,}015d & \text{voor naaldhout} \\ 1{,}30 + 0{,}015d & \text{voor LVL} \\ 0{,}90 + 0{,}015d & \text{voor loofhout} \end{cases} \quad (8.33)$$

Source formulas [13] EC5

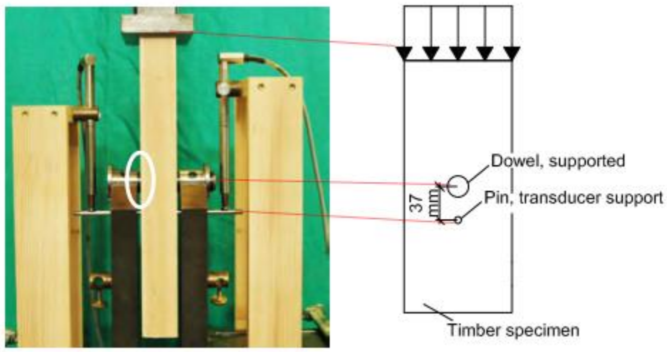
Note: in this research k_{90} will be used for Hardwood(loofhout) instead of LVL. This because the term k_{90} was derived for softwood LVL and not for hardwood LVL.

5.2 *Past research*

In the next chapters articles relevant to this research are shown and discussed.

5.2.1 *Embedment strength beech*

In the test setup below Sandhaas et al[1] tested the embedment strength for beech sawn timber. The goal of this research was developing 3D material for wood but also contained tests on confirming the results of the model. The test setup and results are shown in the figures and tables below.



a) b)

Figure 15 Source[1] setup embedmentest

Table 6-4: Test results embedment tests

Wood species	Dowel diameter	Steel grade	n	Moisture content [%]		f_{emb}(test) [MPa]		Density [kg/m^3]		f_{emb}(vhss) / f_{emb}(hss)	$f_{emb, EC5}$ [MPa]	f_{emb}(test) / f_{emb}(EC5)
				mean	COV	mean	COV [%]	mean	COV [%]			
Spruce	12	hss	7	13.3	10.4	24.6	14.8	482	6.6	1.28	34.8	0.71
		vhss	6	12.7	10.9	31.4	13.9	444	12.4		32.0	0.98
	24	hss	5	12.3	3.1	28.2	8.3	469	5.9	1.35	29.3	0.96
		vhss	5	12.4	2.5	38.0	8.4	463	3.0		28.9	1.32
Beech	12	hss	5	11.8	0.9	46.5	17.0	644	1.5	1.12	46.5	1.00
		vhss	5	11.8	0.8	52.2	6.7	633	3.0		45.9	1.14
	24	hss	5	12.1	6.1	49.8	2.7	725	4.2	1.18	45.2	1.10
		vhss	5	12.0	7.8	58.6	2.3	730	2.4		45.5	1.29

Figure 16 Source[1] Sandhaas et al embedment tests in timber

Tests were done on multiple timber species, the table below selects only a few of the ones executed. During testing 2 types of dowels were used High strength steel(HSS) and very high strength steel. The high strength steel reached results which were very much alike the design formula for embedment strength in the Eurocode, the very high strength steel(VHSS) dowels reached an higher strength. An explanation for this could not be given. This research is used as comparison for comparing the embedment strength of sawn beech with that of LVL-Q and LVL-S.

5.2.2 *Embedment strength LVL-Q and LVL-S*

The amount of information on LVL-Q beech is still limited, however Kobel et al.[2] provides information on dowelled connection on beech LVL-Q. This research was performed on LVL-Q with a cross-layer percentage of 23%. All tensile tests were performed parallel to the grain with different dowel diameters. For some specimen the minimum end distance of 7d(design rule EC5) was reduced to 3.5d. This research was to see whether the end distance of LVL-Q could be reduced. Specimen with 7d end distance showed promising results but 3,5 led to significantly reduced ductility seen in Figure 17 by the curves denoted with (r).

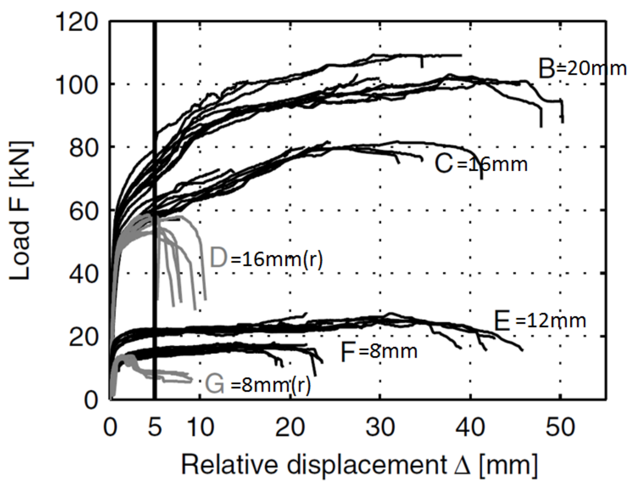


Figure 17 Embedment tests of [2] with modified figure (Dowel diameters are added and (r) indicates reduced end distance of 3.5d)

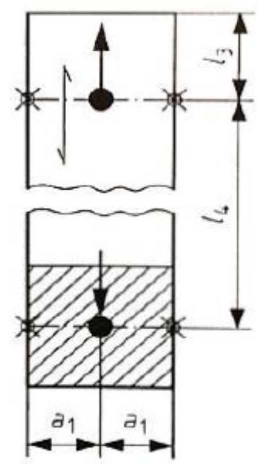


Figure 18 Tensile tests Kobel[2]

In the tensile tests the embedment strength is derived from the maximum strength till 5mm displacement or until failure(EN 383). However these tests the displacement was much higher than expected and at displacements bigger than 5mm the embedment strength continued to increase. This resulted in Kobel listing embedment values at 5mm and at F_{max}. Because LVL-Q is much more ductile than regular timber.

Configuration	$f_{h,\Delta=5mm}$ (EN 383)			$f_{h,max}$			
	n [-]	$f_{h,\Delta=5mm}$ [N/mm^2]	CoV [%]	n [-]	$f_{h,max}$ [N/mm^2]	CoV [%]	$\Delta(F_{max})$ [mm]
B (d=20mm)	10	75	5.1	4	104	2.2	39
C (d=16mm)	8	77	3.6	4	100	5.0	21
E (d=12mm)	10	84	3.4	4	101	4.7	29
F (d=8mm)	10	87	6.7	5	101	4.8	16

Figure 19 Embedment tests results Kobel[2] at $f_{h,5mm}$ and at $f_{h,max}$

Given the results by Sandhaas et al[1] the embedment strength of beech is around 46.5-52.5(N/mm^2)(The range is the difference between HSS dowels and VHSS dowels). Reaching a strength of 84N/mm^2 at a displacement of 5mm and a strength of 100N/mm^2 at max displacement. LVL-Q seems to be significantly stronger, and not only strength but also ductility increases. While beech starts to fail around a displacement of 6mm, (see Figure 20) LVL seemed to maintain its strength up to 40mm of displacement(Figure 17).

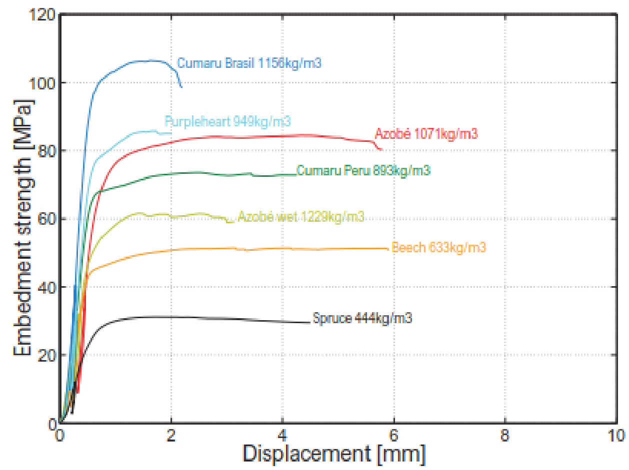


Figure 20 [1] Sandhaas Mean stress-deformation curves per series, 12mm vhss dowels(for test setup see Fout! Verwijzingsbron niet gevonden.**)**

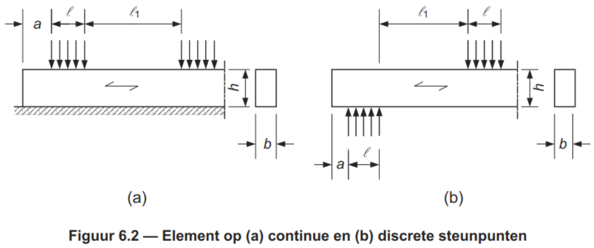
This research was later followed up by another research which included the addition of different cross layers.

Table 3 Results of embedment tests according to EN 383.

	Configuration			f_h acc. to EN 383 ($w \leq 5$ mm)				f_h from maximum load F_{max}			
	Cross-layers [%]	Dowel diameter [mm]	End dist. [mm]	$f_{h,EN383,mean}$ [N/mm²]	$w_{mean}(F_{EN})$ [mm]	n [-]	CoV [%]	$f_{h,max,mean}$ [N/mm²]	$w_{mean}(F_{max})$ [mm]	n [-]	CoV [%]
Acc. to EN 383:2007	23	8	7*d*	87	5.0	10	6.7	101	16.0	5	6.7
	0	12	7*d*	72	2.1	5	3.5	72	2.1	5	3.5
	17	12	7*d*	84	4.8	10	1.9	93	25.7	5	2.6
	23	12	7*d*	84	5.0	10	3.4	101	29.0	4	3.4
	0	16	7*d*	62	2.1	5	7.8	62	2.1	5	7.8
	14	16	7*d*	75	5.0	10	8.6	89	22.0	5	5.2
	23	16	7*d*	77	5.0	8	3.6	100*	21.0*	4	3.6*
	23	20	7*d*	75	5.0	10	5.1	104	39.0	4	5.1
l_3 reduced	0	12	5*d*	49	0.4	5	5.8	49	0.4	5	5.8
	17	12	5*d*	86	4.1	9	2.0	86	4.9	5	2.1
	0	16	5*d*	55	0.6	5	2.7	55	0.6	5	2.7
	14	16	5*d*	71	4.9	6	2.6	74	8.4	5	2.9
	23	8	3.5*d*	81	1.4	5	2.6	81	1.4	5	2.6
	23	16	3.5*d*	72	4.6	7	3.9	71	5.0	5	4.7

Figure 21 source[15] results of embed tests Kobel et al

A lower amount of cross layers from 23% to 14%(see Figure 24) affected the embedment strength at large displacements, however the strength at a displacement of 5mm seems to be very much equal. This is likely cause by the same rope effect which is seen by loading timber in compressions perpendicular to the grain. Which is taken into account by increasing the effective load area times a coefficient $k_{c,90}$.



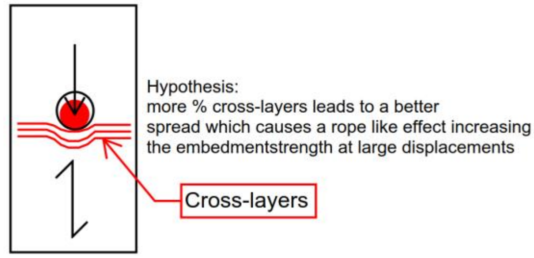


Figure 22 Source[13] compressions perpendicular to the grain in EC5

Figure 23 Hypothesis on why the embedment strength is higher with a higher % of cross-layers in LVL-Q

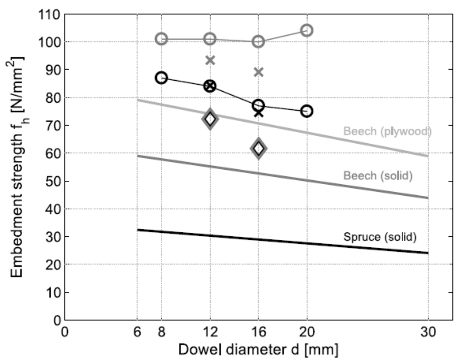


Figure 24 Embedment strength comparison with: O=23%; X=14% ◊= 0%; O,X,◊(black) are according to f_h of EN383; O,X,◊(grey) are f_h max [3]

In [15] can be seen that beech LVL-S(0% cross lamination) fails in splitting instead of shear or embedment strength as seen below. Which shows that the perpendicular reinforcements helps against splitting in the connections. The embedment strength in these connections were also significantly lower at 72N/mm^2.

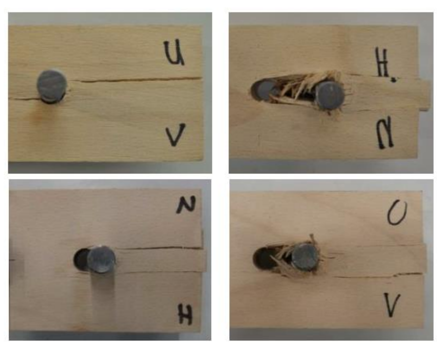


Fig. 7 Failures from embedment tests. Top left: 0-12-7*d*; top right: 17-12-7*d*; bottom left: 14-16-5*d*; bottom right: 14-16-7*d* (labels as in Table 3).

Figure 25 source [15] failures modes in experiments of kobel et al(

5.2.3 LVL-S connections in FM-II

In the test below bij Misconel et al[16] tests are shown for tests on LVL-S. The setup was done for 1,2 and 3(HM 1,HM2, HM3) dowels in a row and a setup of 2*3(HM6) dowels in row. This to analyse the load carrying, ductility and stiffness and whether the current design rules of the Eurocode fit[16]. In the tests the mild steel dowels resulted in a lower load carrying capacity but in combination with multiple fasteners for a better ductility. The VHSS steel dowels resulted in the opposite as seen in the graphs in Figure 28.

This research gives a good view of how VHSS dowels react in an dowelled connection in FM-II. And shows that in FM-II the ductility is limited both in the use of mild steel and VHSS steel.

***Figure 1:** Detail of a joint specimen*

Figure 26 source[15]

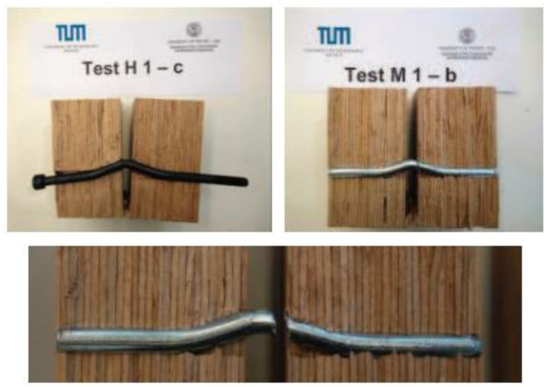


Figure 27 source[15] failure mode II/II in T-S-T connnections

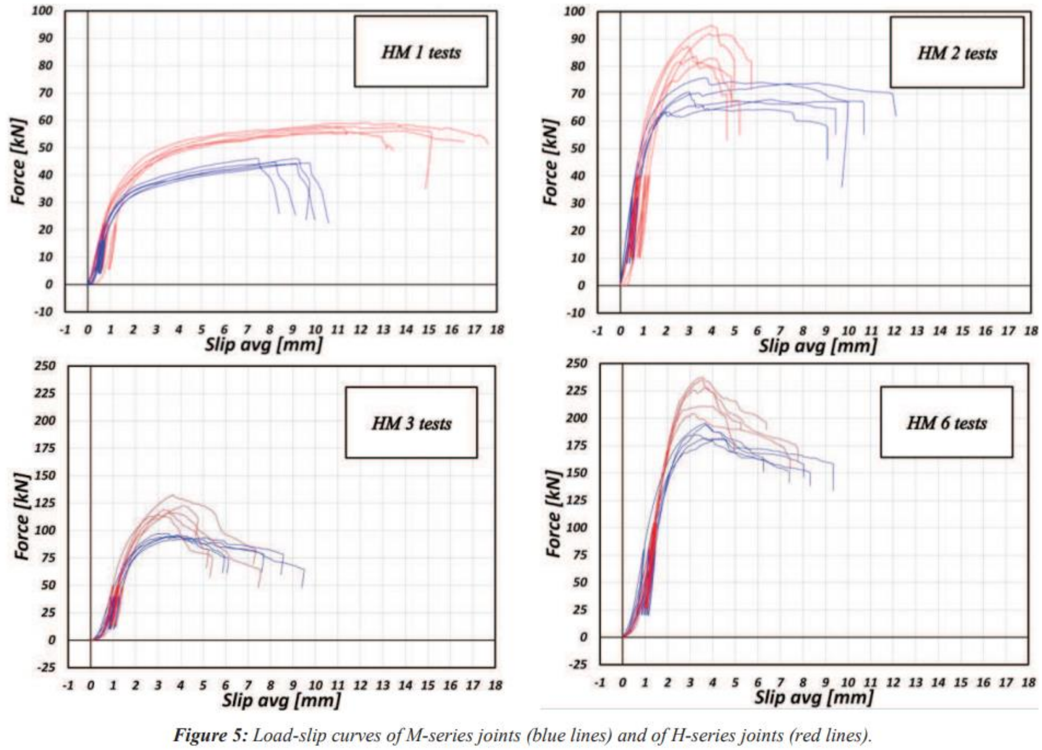


Figure 28 Source [15] Force displacement diagrams for dowelled connections in LVL-S(for dowel diameter =10mm and mild steels(blue lines) and high strength steel red lines)

For multiple dowels in line the observed reduction for n_{ef} was observed to be about similar to that of design rules by the Eurocode.

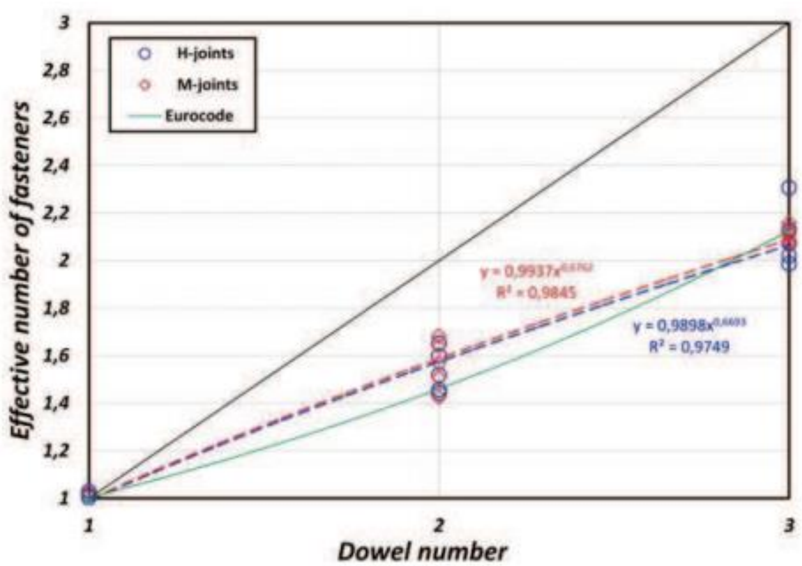


Figure 29 source [16] Effective number of fasteners in connections in beech LVL-S

5.2.4 Embedment strength plywood

For reasons unknown very hard to acquire information on experimental results of beech/spruce plywood. As an alternative for this master thesis the results from Jumaat et al[17] will be used. This research included tests on Malaysian hardwood plywood. The density of the woodspecies "Kempas" is the closest to that of beech. While a similar density is observed the ductility is unlike that of beech, as beech is significantly more ductile. While it's not exact results come relatively close to that of the EC5 when using equation the equation below and thus will be confirmed as an appropriate comparison for later analysis. *Note that the test setup used deviates from EN 383 standards, and will give slightly different results.*

$$f_{h,k} = 0{,}11(1 - 0{,}01d)\rho_k \qquad (8.36)$$

f_h=0.11*(1-0.01*8)*782.57=79N/mm^2 for Kempas plywood dowel diameter 8

f_h=0.11*(1-0.01*8)*637.93=64N/mm^2 for Mengku Lang plywood dowel diameter 8

Equation 1 Embedmentstrength design formula for plywood

Fig 1 Test set-up

Figure 30 Source [17] Test setup for embedment tests on plywood

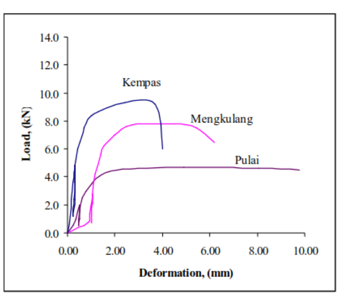


Fig 2 Load deformation curve

Table 1 Summary of test results

Species	Dowel diameter (mm)	Total samples	Average F_{max} (kN)	Average f_h (N/mm^2)	Density (kg/m^3)	Moisture content (%)
Kempas	6	15	6.32	87.78	887.59	11.05
	8	15	11.12	86.88	782.57	10.96
	12	15	24.81	86.15	866.02	11.31
Mengku lang	6	15	4.41	61.29	663.14	12.43
	8	15	7.59	59.28	637.93	12.21
	12	15	17.06	59.23	677.82	11.05
Pulai	6	15	2.71	37.64	450.42	11.02
	8	15	4.73	36.95	449.66	11.80
	12	15	8.69	30.17	377.49	10.36

Figure 31 Source [17] test results for embedment tests on plywood

5.2.5 Strength properties LVL

For a comparison of the most influenced mechanical properties, four different timber products have been selected. Solid beech strength class D40. This strength class is defined by the grading according to the DIN 4074 LS13. The other compared values are LVL-S and LVL-Q with both 14% and 28% cross lamination(strength values by product specifications next page). The two different percentages are chosen as they are both used during this research.

What we can see in Figure 32 is that the bending strength of LVL-S beech is significantly higher. LVL-Q which is weakened in longitudinal direction due to cross lamination has a higher strength than solid beech. This shows the benefit of LVL compared to regular sawn timber. The perpendicular tensile strength of LVL-Q(in plane) is tremendously strengthened compared to sawn beech or LVL-S(see Figure 33).

The strength of LVL is enhanced due to various reason.

- Densification of the LVL(Dependent on pressure, initial moisture content)(Chui et al[18])
- Type of resin used and whether veneers are impregnated(Chui et al[18])
- Aligning the veneers in the same direction

This research focuses however on the embedment behavior in timber LVL-Q, and will not go into full detail of why LVL is stronger than regular timber.

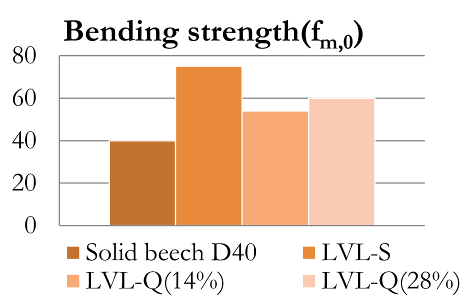


Figure 32 Bending strength(edgewise) comparison.

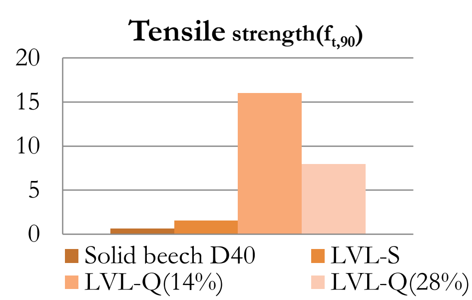


Figure 33 Characteristic tensile strength(edgewise) comparison

Note: Charactertic values(5%) obtained by either EN338 or baubuche product specifications

Below the product specification used for this research.

Table 3: Characteristic strength and stiffness values in N/mm² and density in kg/m³

Type of load		Board BauBuche S Laminated veneer lumber "Beech LVL with longitudinal layers"	Board BauBuche Q Laminated veneer lumber "Beech LVL with crosswise layers"	
Nominal thickness in mm		$20 \leq B \leq 80$	20 [a)]	$30 \leq B \leq 80$
Strength values				
Flatwise bending				
Bending	$f_{m,0,flat,k}$	80	70	75
	$f_{m,90,flat,k}$		32	20
Compressive	$f_{c,90,flat,k}$	10 [c)]	13 [c)]	
Shear	$f_{v,0,flat,k}$	8	3,8	
Edgewise bending				
Bending [b)]	$f_{m,0,edge,k}$	75	54	60
	$f_{m,90,edge,k}$		18	10
Tensile ∥ to the grain	$f_{t,0}$	60	45	51
Tensile ⊥ to the grain	$f_{t,90,edge,k}$	1,5	16	8
Compressive ∥ to the grain	$f_{c,0,k}$	57,5 [c)]	45,6 [c)]	53,3 [c)]
Compressive ⊥ to the grain	$f_{c,90,edge,k}$	14	37 [c)]	19 [c)]
Shear	$f_{v,0,edge,k}$	8	7,8	

Figure 34 Used product specifications Pollmeier Baubuch LVL

6 Experiments

The increased embedment strength as shown in the literature study combined with the higher resistance to splitting led to the idea whether it's possible to design a moment resisting joint in LVL-Q which receives its ductility by using the deformation of the timber instead of the fastener. This requires failure mode I which would mean that the dowel is to remain straight during the experiments and unable to form any plastic hinges. This is done as FM-I generates the highest shear force per thickness t of timber, and because the deformation capacity of LVL-Q is promising.

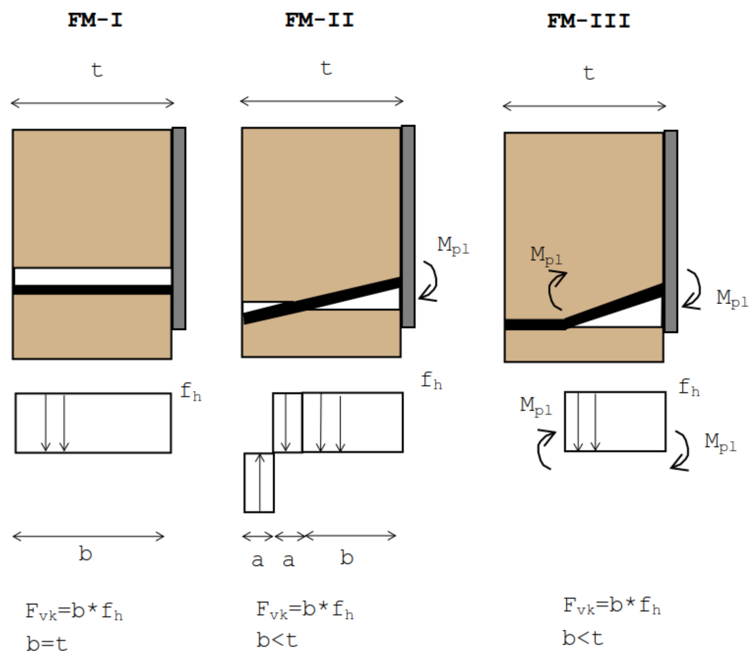


Figure 35 illustration of why FM-I is always stronger per thickness t of timber

The goal is to achieve:

- High n_{ef} because deformation capacity/ductility of the timber
- High load carrying capacity efficiency in the dowels per timber thickness t

This is done to answer the research question:

Is it possible to design a moment resisting connection in LVL-Q timber which has a higher moment capacity than the moment capacity of the timber its connected to?

For this the following test setup is designed and is explained on the following paragraph:

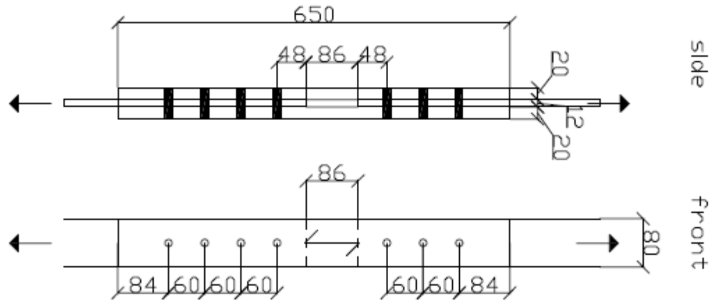


Figure 36 Principle test setup and dimensions

To answer the research questions:

- ***What is the behavior of dowelled connections in LVL-Q and how does this change in different loading angles to the grain?***
- ***Does splitting occur for end distances as given by the Eurocode 5 and can these be reduced?***
- ***What is the influence on the load carrying capacity of the dowels when multiple dowels are used.***

6.1 Tests

The following tensile tests have been proposed with their respective end distance, number of dowels and direction of loading.

Tests have been set up based on 2 thicknesses t=20mm and t=40mm. Thickness 20mm is used for FM-I and thickness t=40mm is used for FM-II. The focus of this research is on FM-I but FM-II serves as a comparison for the ductility. Also it generates additional results and perhaps other insights.

The choice was made for VHSS(very high strength steel f_y=1080N/mm^2) dowels because the embedment strength was expected to be very high. Even for a small thickness of t=20 the dowels are close to forming an plastic hinge.

Number of dowels	0° end=7d	45° end=5.65d*	90° end=4d
N=1	5	5	5
N=2	5	-	5
N=3	5	-	5
Total tests	15	5	15

Table 1 Number of specimen for LVL-Q-t=20mm and VHSS-12mm

**end distance of 5.65d is based on a moment resisting connection in a square pattern with an end and edge distance of 4d. The distance of the dowel to the corner of the loading direction is approximately 5.65d.*

Number of dowels	0° end=5d	45° end=-	90° end=-
N=1	5	-	-
N=2	5	-	-
N=3	5	-	-
Total tests	15	0	0

Table 2 Number of specimen for LVL-Q-t=20mm and VHSS-12mm (reduced end distance to 5d)

Number of dowels	0° end=7d	45° end=-	90° end=-
N=1	2	-	2
N=2	2	-	2
N=3	2	-	2
Total tests	6	0	6

Table 3 Number of specimen for LVL-Q-t=40mm and VHSS-12mm

The LVL-Q used is produced by Pollmeier and corresponds with the layout noted in Figure 37(20mm and 40mm).

Nominal component thickness in mm	Number of veneer layers longl	crossw.	total	Composition
20	5	2	7	I-III-I
30	9	2	11	II-IIIII-II
40	12	2	14	III-IIIIII-III
50	16	2	18	III-IIIIIIIIII-III
60	17	4	21	III-II-IIIIIII-II-III
70	20	4	24	III-II-IIIIIIIIII-II-III
80	23	4	27	III-II-IIIIIIIIIIIII-II-III
I longitudinal veneer layer				
- crosswise veneer layer				

Figure 37 properties Baubuche-Q

6.2 Used materials

Proposed experiments in Table 1 and Table 2 are to observe the embedment behavior of dowel failing in FM-I. This allows for a good observation of the embedment strength. It also makes for a better comparison of timber properties as the final strength of the connection is not/barely influenced by the dowel properties.

For these tests a thin LVL-Q with a cross layer percentage of 28.8% is used. This is on the high side but there were only 2 thicknesses available 20mm and 40mm(14.4% cross-layer). The 40mm thickness unfortunately led to FM-II with dowel diameter 12mm. A solution could be to increase the dowel diameter but this led in turn to the possibility of the capacity of the connection exceeding the strength of the test equipment. Thus to stay within the margin of not exceeding the test equipment while still maintaining FM-II required a thin thickness of timber and a high steel strength. Due to dowels not being available in strength exceeding $1000N/mm^2$ the smooth shaft of bolts strength 12.9 is used. With the head and thread not touching the timber.

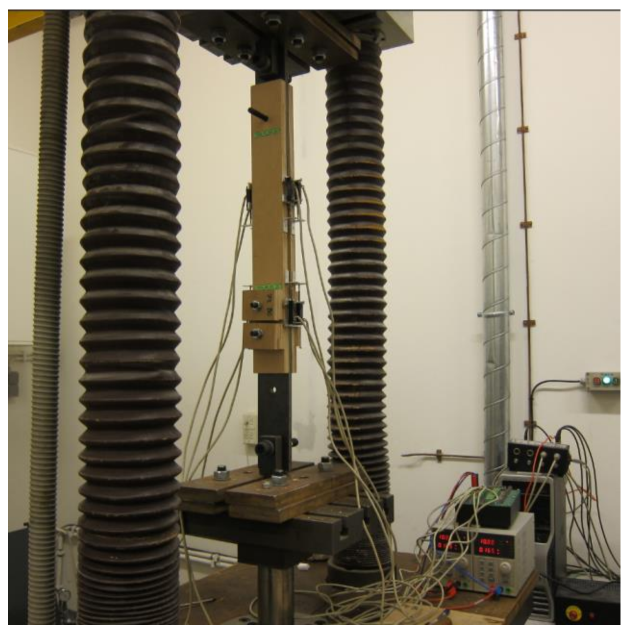


Figure 38 Test setup

Tests proposed in Table 3 are failing in FM-II, these tests use the same steel quality but a different timber thickness which is the 40mm variant(14.4% cross layer). This failure in FM-II can be used as a comparison of the deformation capacity of connections failing in FM-II compared to FM-I. As this is one of the goals of this research to see whether it's possible to design a ductile connection failing in FM-I instead of FM-II.

6.3 Test Setup

The test equipment makes use of an existing setup. The steel plate, bolts and I-shaped connectors are used to mount the experiment to the jack have also been using during other tensile tests. During the experiments only the timber and number of dowels will vary. The same steel plate will be reused unless damaged. The test setup shown is for testing 3 dowels parallel to the grain. An additional dowel is placed at the top to ensure failure occurs at one side of the test equipment.

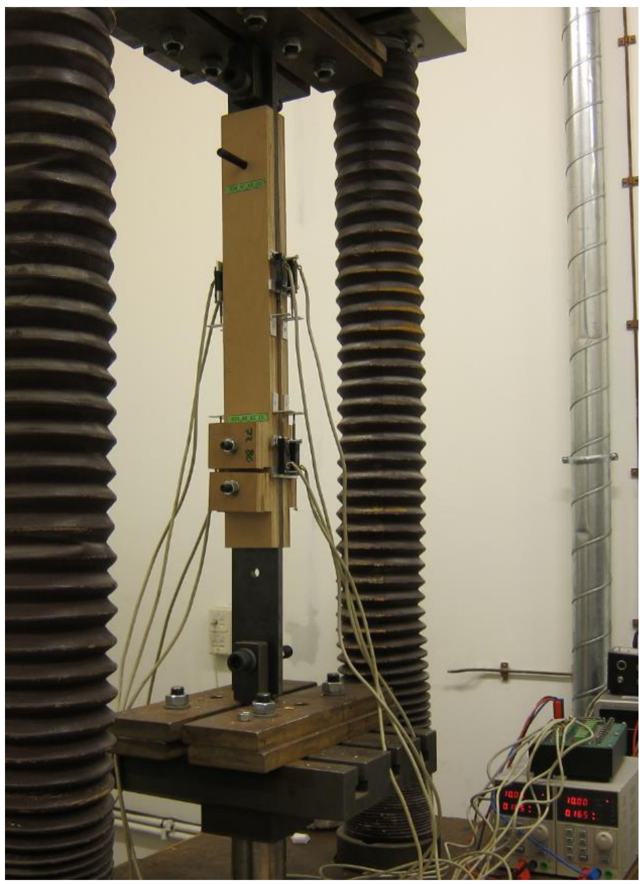


Figure 39 Test setup as used during experiments(Above experiment T20_A0_N1)

6.4 Load procedure

The load procedure for mechanical fasteners according to NEN-ISO 6891:1991 will be used. Figure 40 shows this procedure. This is based on the expected maximum load. This can readjusted after 1 or multiple tests have been done. Loading will be raised to 40% of the expected capacity, than unloaded back to 10% and raised again up to failure.

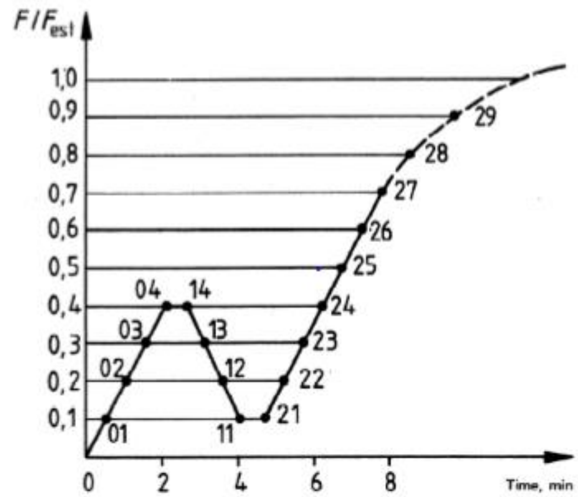
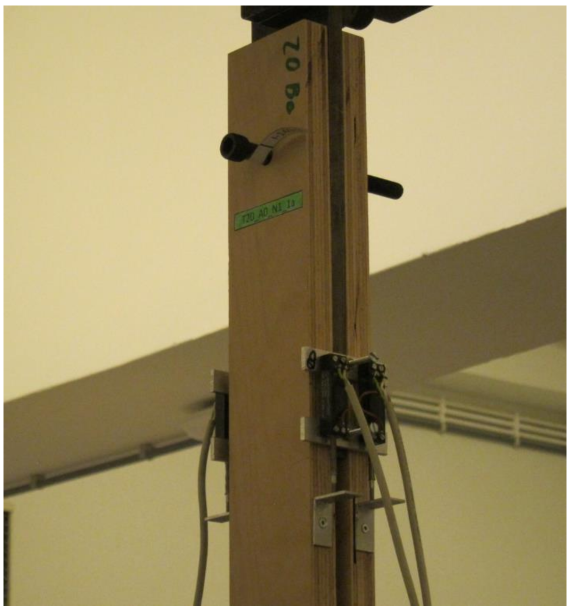


Figure 40 Load procedure according to NEN-ISO 6891:1991

6.5 Measuringdata

The devices used for measurement linear variable differential transformers (LVDT's) four of them are attached with screws to the timber with the springs resting on an L-Shaped steel plate. The LVDT's are connected to the steel plate while the L-shaped supports are attached to the timber. The difference of one side of the timber is measured by averaging the deformation of the 4 LVDT's. The maximum displacement that can be measured is 25mm, there is a chance that this is exceeded which prevents any measurement at larger distances. This is not an issue as is decided to hold the experiments after a displacement of 15mm at which the deformation is deemed sufficient. This is further illustrated in the pictures and impressions below.



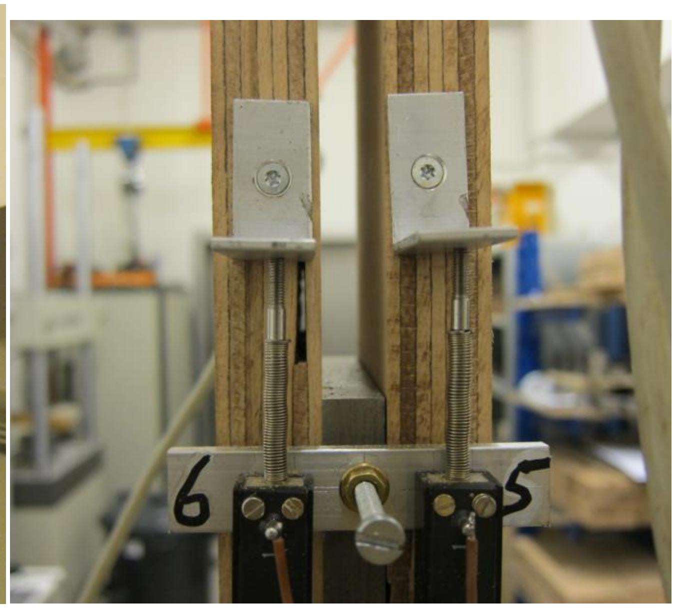


Figure 41 Measurement of deformation using LDVT's

Figure 42 Closeup LVDT's

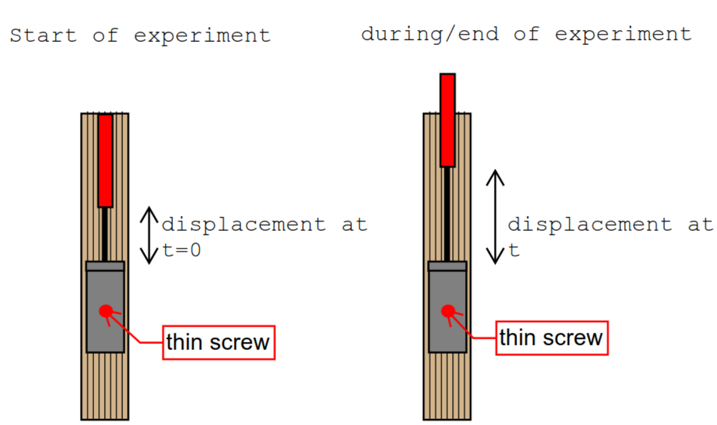


Figure 43 Impression of measure displacement of connection using LVDT's.

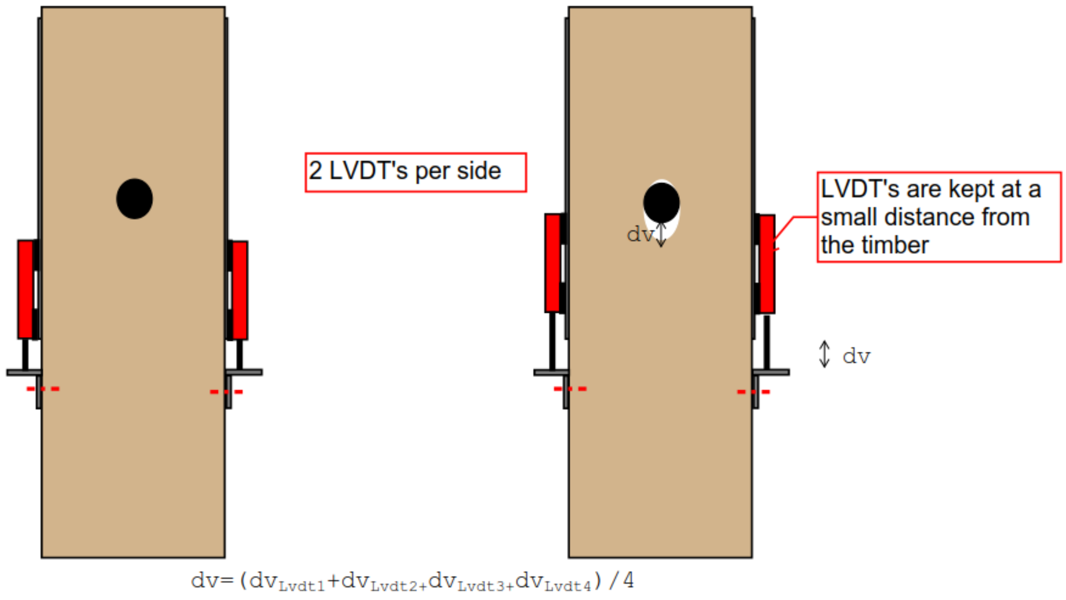


Figure 44 Impression of measurement displacement of dowels

6.6 *Embedment strength EN 383*

The EN 383 is applicable for LVL as the scope is defined by the citation below. However it remains arguable that if a very large embedment deformation is expected that it is measured at where F_{max} occurs(see Equation 2). Kobel[2] et al started to determine the embedment strength at 5mm and F_{max} and noted that the EN 383 is mainly made for solid wood which is rather brittle[15].

1 Scope

This standard specifies laboratory methods to determine the embedding strength and foundation values of solid timber, glued laminated timber and wood based sheet products with dowel type fasteners.

Source[14] EN 383

$$f_h = \frac{F_{max}}{dt} \qquad (1)$$

Equation 2 Determination of embedment strength according to EN 383[14]

There are currently no guidelines but the deformation capacity of regular timber Figure 20 is around this value of 5mm. That's why I believe that this is an practical value at which the embedment strength is determined. Hence in this report will often be refered to F_{max} and F_{5mm}. The extra benefit is that comparisons are easier to make with that of Kobel et al[2]

6.7 Materials and sorting

6.7.1 Preparation test specimen

Timber was supplied by pollmeier in large plates and sawed into pieces and brought to the timber workshop. There it was it was sawn into the appropriate dimensions. The dimensions can be found in the drawings paragraph. The length of every specimen is 650mm and the width is dependent on how the specimen is loaded. This is 80mm(parallel), 170mm(45° degrees angle) and 240mm(perpendicular) respectively depending on the type of loading. The pictures below show shortly the procedure of sawing the timber into pieces and how the holes were drilled. Pictures are in chronological order and show the procedure.

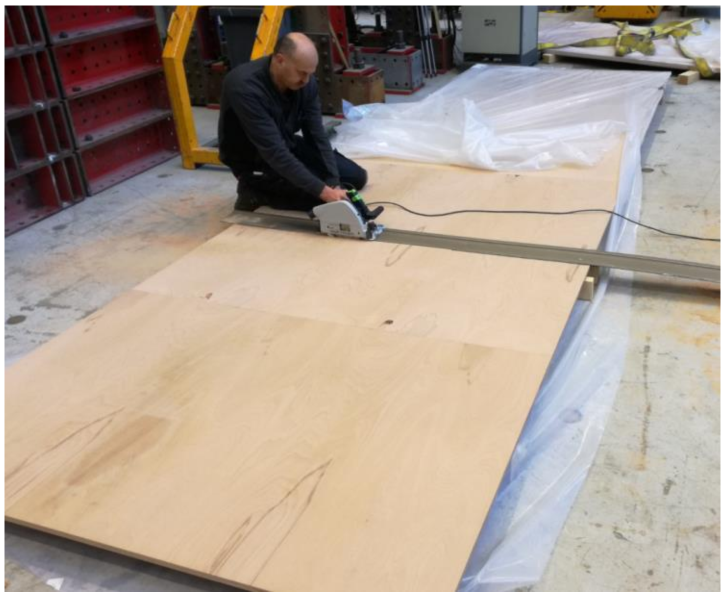


Figure 45 LVL-Q plates as ordered sawn into smaller plates for use in timber workshop

Figure 46 LVL-Q plates were put onto the saw table to saw them into chosen dimensions

Figure 47 LVL-Q specimens(width 240mm)

Holes are drilled with a diameter of 12,5mm to prevent misalignment of the dowels(12mm). This will cause some hole clearance but this is in practice also the case.

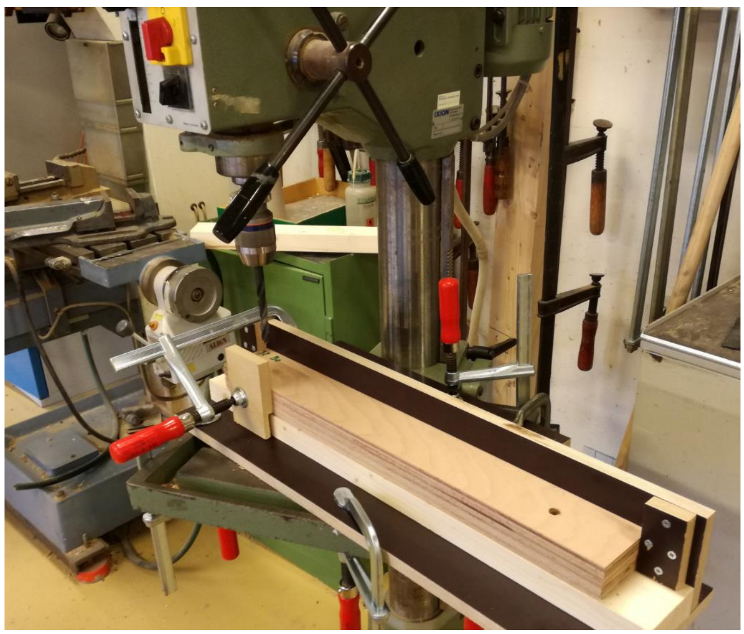
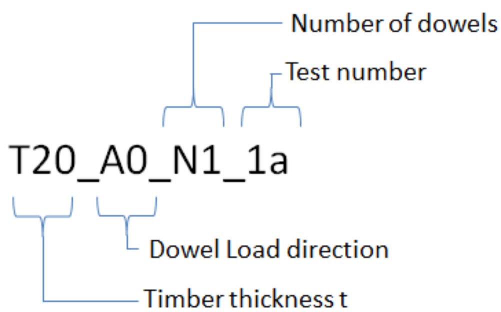


Figure 48 Drilling of dowel holes with drill(specimen 80mm width)

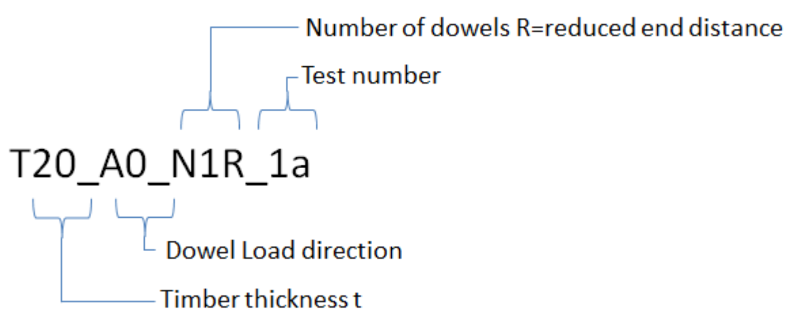
During the sawing of the timber the location of where they were sawn out of the plate is recorded. This drawing is attached into the appendix(Figure 163 and Figure 164).

6.7.2 Coding

Each specimen is given a code after sorting, the code is as follows.



Each tests consists of (a) and a (b) part this are two timber beams which make one full connection. Some codenames also include the R in the number of dowels section this means that the end distance is reduced for these specimen.



6.7.3 Density

After sawing the timber in the dimensions, the timber dimensions and weight have been measured. These values can be found in table 34 to table 38. Each specimen has been measured using a digital caliper at the top and at the bottom, to account for any sawing errors. The average of the two values determines the thickness or width. Very little variation was found so this was not necessarily required. The length has been measured using a tapeline and is thus less accurate but also of less importance during experiments.

Data shows that LVL-Q with a thickness of 20mm show more variation than LVL-Q of 40mm. Both don't vary much but the variation is significantly lower for LVL-Q with a thickness of 40mm. The mean density of 40mm LVL timber is slightly higher than that of 20mm LVL. This most likely has to do something with the production process but why this is exactly is not clear. The distribution can be found in Figure 49 Bar graph of density distribution of sawn LVL-Q.

Thickness (mm)	Standard deviation $\sigma_{st}(kg/m^3)$	Mean density $\rho_m(kg/m^3)$	Coefficient of variance (-)
20	18.8	786	2.4%
40	7.5	811	0.9%

table 4 Mean density and standard deviation of the timber

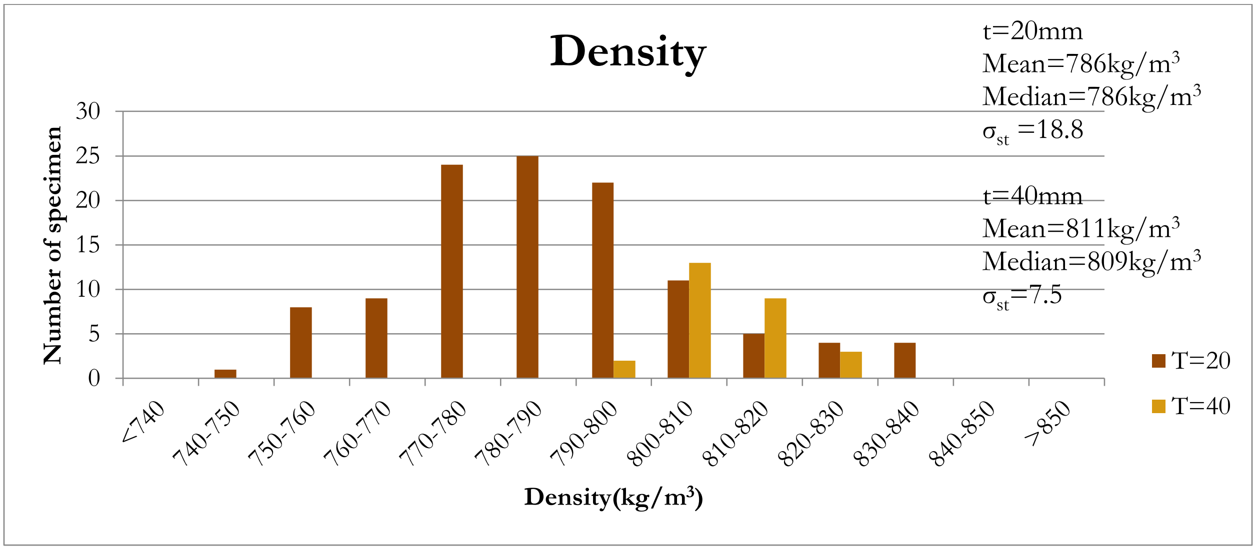


Figure 49 Bar graph of density distribution of sawn LVL-Q

During sawing of the timber the amount of material sawn was more than was expected. Therefor specimen that are not used have been sorted out of the used material. These specimen were outliers in the density curves and where manually selected. This resulted in removing the lowest and highest density specimen until the right number of specimen were acquired. This was done manually.

Test specimen are sawed in 5 different dimensions with the following tests:

- 650x80x20 N=1,2,3 and two different end distances total unique test variants: 6
  - T20_A0_N1,2,3 and T20_A0_N1R,N2R,N3R
- 650x170x20 N=1 and one end distance total unique test variants: 1
  - T20_A45_N1
- 650x240x20 N=1,2,3 and one end distance total unique test variants: 3
  - T20_A90_N1,2,3
- 650x80x40 N=1,2,3 and one end distance total unique test variants: 3
  - T40_A0_N1,2,3
- 650x240x40 N=1,2,3 and one end distance total unique test variants: 3
  - T40_A90_N1,2,3

Each beam dimension is sorted from lowest to highest and distributed among the different test variants. They were selected in pairs so the two lowest density specimen were put for example into group T20_A0_N1 for the next in T20_A0_N2 etc. This to keep the densities of each group as close as possible.

Test specimens	Number of specimen (-)	Average Density test specimen (kg/m^3)
T20_A0_N1	5	783.0
T20_A0_N2	5	784.4
T20_A0_N3	5	786.2
T20_A0_N1R	5	787.5
T20_A0_N2R	5	790.1
T20_A0_N3R	5	792.0
T20_A45_N1	3	793.1
T20_A90_N1	5	778.9
T20_A90_N2	5	782.1
T20_A90_N3	5	784.0
T40_A0_N1	2	809.5
T40_A0_N2	2	813.9
T40_A0_N3	2	818.2
T40_A90_N1	2	808.0
T40_A90_N2	2	811.9
T40_A90_N3	2	814.5

table 5 Test variants numbers and average density

Each test specimen was sawn out of a LVL-Q plate. For this there was a saw numbering with an individual number. After weighing and measuring the specimen these have been reordered. The original saw order can be found in the appendix(table 39 Codenames for test specimen N= sorted on density, for dimensions 650x80x20(length x width x thickness)(table 39 to table 54)

6.7.4 Steel plate and fasteners

The steel plates used for the experiments are used in earlier research. Some holes see some deformation but this is minimal. Therefor the steel plates are assumed to be undamaged and reused for experimentation. The steel quality is S355 and the thickness of the elements are 12mm. Dimensions are as in Figure 50 and Figure 51.

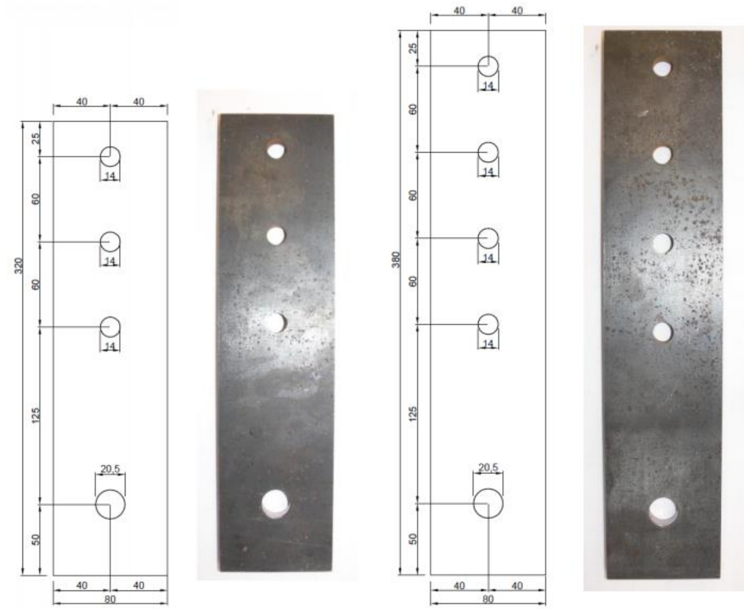


Figure 50 Steel plates used, drawings and pictures source[4]

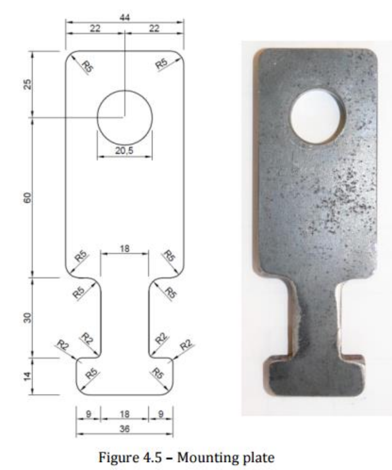


Figure 51 Steel connecters used, drawings and pictures source[4]

7 Calculations test setup

7.1 Designing LVL test specimen

The dimensions of the test specimen have been designed that the timber fails in failure mode I and failure mode II. As was explained in chapter 4. With the experiments of Kobel et al[2] showing very large displacements in FM-I the idea was to design a moment resisting connection which gains its ductility by the deformation of the timber instead of the dowel.

Kobel et al[2] determines the determines the embedment strength mainly at 2 points. At 5mm a low displacement and at the displacement at which F_{max} is reached. Since F_{max} can occur at a very large displacement of 20mm which is very rare for regular timber an additional point for determination of the embedment strength is used. Which is the embedment strength at a displacement of 5mm. This is used multiple times in this research.

7.1.1 Embedment strength

To predict the strength of the LVL values of [2] are used to predict the possible strength of the LVL with cross layers. Strength varies on dowel diameter and LVL cross percentages. Also the veneer layout could make a difference hence the prediction of strength will be not be entirely accurate. But still quite accurate in the determination of the dimensions of the test equipment.

For the experiments two types of timber LVL-Q will be used.

- LVL-Q with thickness 20mm and a cross layer percentage of 28%
- LVL-Q with thickness 40mm and a cross layer percentage of 14%

Values of 23% and 17% are the closest to these experiments and will be used to predict the strength. For this an 95% confidence interval is used. For failure mode I only an upper boundary of the embedment strength is necessary as this indicates the shift from failure mode I to II. Embedment strength much lower than expected will still lead to FM I.

Crosslayer percentage(%)	Dowel diameter(mm)	f_h(N/mm^2)	CoV(%)	f_{hmin}(n/mm^2)	f_{hmax}(n/mm^2)
17	12	84	1,9	81	87
23	12	84	3,4	78	90
14	16	75	8,6	62	88
23	16	77	3,6	71	83

table 6 Embedment strength at 5mm displacement (small deformation)source values:[2]

Crosslayer percentage(%)	Dowel diameter(mm)	f_h(N/mm^2)	CoV(%)	f_{hmin}(n/mm^2)	f_{hmax}(n/mm^2)
17	12	93	2,6	88	98
23	12	101	3,4	94	108
14	16	89	5,2	80	98
23	16	100	3,6	93	107

table 7 Embedment strength at more than 5mm(large deformation)source values:[2]

For prediction of failure mode I and failure mode II the following values will be used

$f_{h,min} = 62N/mm^2$
$f_{h,max} = 108N/mm^2$

7.1.2 Failure mode

The strength per shear plane is based on the Johansen equations which are the following.

$F_{v,rk} = f_h * t_1 * d$ for FM I

$F_{v,rk} = f_h * t_1 * d * [\sqrt{2 + 4 * \frac{M_y}{f_{h*d*t_1^2}}} - 1]$ for FM II

$F_{v,rk} = 2\sqrt{M_y * f_h * d}$ for FM III

The minimum(governing) equation will indicate the failure mode. Possible scenarios between embedmentstrength and steel strength are used to predict the possible scenarios. For both material properties a 95% confidence interval is used.

f_h(N/mm^2)	f_u(N/mm^2)	t(mm)	d(mm)	My(Nmm)	F_v(FM-I)(kN)	F_v(FM-II)(kN)	F_v(FM-III)(kN)
62	1075	20	12	309600	14,9	22,1	30,4
62	1573	20	12	453024	14,9	27,4	36,7
108	1075	20	12	309600	25,9	28,4	40,1
108	1573	20	12	453024	25,9	34,8	48,5
62	1075	40	12	309600	29,8	22,1	30,4
62	1573	40	12	453024	29,8	26,1	36,7
108	1075	40	12	309600	51,8	31,7	40,1
108	1573	40	12	453024	51,8	36,0	48,5

table 8 Strength of failure mode I-III with varying embedment strength and steel strength

In which FM I is always governing for 20mm thickness I and FM II always governing for 40mm thickness which is as required.

7.1.3 Dimensions

Maximum dowel load per single dowel(see table 8):

- For 20mm thickness: F_{vd}=25.92kN
- For 40mm thickness :F_{vd}=36.0 kN

	t=20mm	t=40mm
$f_{t,0}$	45N/mm^2	51N/mm^2
$f_{t,90}$	16N/mm^2	8N/mm^2

table 9 Tensile strength LVL-Q for thickness 20mm and 40mm

Tensile capacity net cross section:
$F_{R,t} = (w - d) \cdot t \cdot f_t$

Load direction (°)	Dowel diameter d (mm)	Thickness t (mm)	Width W (mm)	Characteristic tensile strength f_t (N/mm^2)	Tensile capacity $F_{R,t}$ (kN)
0	12	20	80	45	61,2
90	12	20	240	16	72,96
0	12	40	80	51	138,72
90	12	40	240	8	72,96

table 10 Tensile capacity timber

Unfortunately a mistake was made in determination of the dimensions. When checking the tensile strength the shear strength of the connection exceeds that of the net-cross section of the timber. In this table is checked whether it was possible that with a lower n_{ef} whether it was possible that the failure would not occur.

Tensile capacity $F_{R,t}$ (kN)	Dowel load per shear plane F_{vk}	Number of dowels n (-)	Unity check $\frac{F_{vk} \cdot n}{F_{R,t}}$	Effective number of dowels $n_{ef,Research\ Sandhaas}$ (-)	Unity check $\frac{F_{vd} \cdot n_{ef}}{F_{R,t}}$
61,2	25,92	1	0,42		
61,2	25,92	2	0,85		
61,2	25,92	3	1,27	2,5	1,06
72,96	25,92	1	0,36		
72,96	25,92	2	0,71		
72,96	25,92	3	1,07	2,5	0,89
138,72	36	1	0,26		
138,72	36	2	0,52		
138,72	36	3	0,78	2,5	0,65
72,96	36	1	0,49		
72,96	36	2	0,99		
72,96	36	3	1,48	2,5	1,23

Table 11 Unity check tensile capacity for n_{ef}=n and for n_{ef}=$n_{ef,research\ sandhaas}$

Three of them don't meet the unity check, this could lead to tensile failures which are not wanted. This tensile failure is not guaranteed but could occur which is unfortunate but can't be undone as the material is sawn.

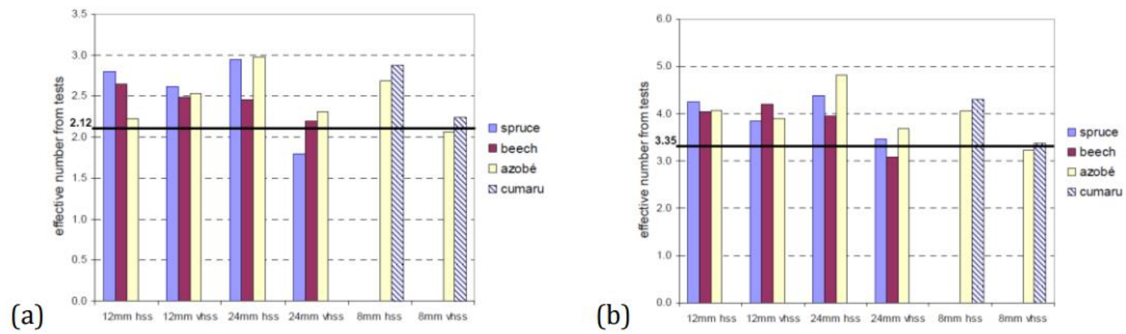


Figure 52 Effective number of fasteners from tests; (a) Joint test with 3 dowels per row (b) joint tests with 5 dowels per row[3]

Expected is at least 2,5 but most likely even higher due to the amount of crosslayers.

$$n_{ef} = \min \begin{cases} n \\ n^{0,9} \sqrt[4]{\dfrac{a_1}{13d}} \end{cases}$$

Based on Eurocode 5 formula the n_{ef} would be:

$$n_{ef} = n^{0.9} \sqrt[4]{\frac{a_1}{13d}} = 3^{0.9} \sqrt[4]{\frac{60}{13 \cdot 12}} = 2.117 = 2.12$$

However the more likely values are as found by Sandhaas shown in Figure 52.

The embedment strength used in this calculation is 108N/mm^2 which is a very high embedment strength. Much higher than is usually the case for sawn beech which is around (measured 800kg/m^3 density of sawn LVL-Q beech).

$$f_h = 0.082 \cdot (1 - 0.01d)\rho_k = 0.082 \cdot (1 - 0.01 \cdot 12) \cdot 800 = 57.7N/mm^2$$

The unity check do not meet the required conditions however it could still be possible that the test go as planned for 3 dowels:

- Characteristic tensile strength has been used which is the 5-percentile value of the tensile strength if fortunate this is a little bit higher
- Embedment strength does not reach the maximum values as predicted(very likely in all dowels acting perpendicular to the grain)
- Effective number of dowels does not become higher for LVL-Q

All tests with 1-2 dowels should not see any problems and meet the required resistances, tests with 3 dowels could fail due to tensile failure due to a calculation error.

7.1.4 Edge distances

Minimum a_4 for a force parallel to the grain according to EC5: Max((2+2 sin α)d; 3d) with only the term 3d governing for dowel diameters 12mm. Leads to a minimum width of 2 a_4. The minimal width of the connection to meet the edge distance requirement:

- $w_{min,12,0}$=2*12*3=72mm <80mm

Minimum a_3 for a force perpendicular to the grain according to EC5: Max(7d; 80mm) with only the term 7d governing for dowel diameters 12mm. Leads to a minimum width of 2 a_3. The minimal width of the connection to meet the edge distance requirement:

- $w_{min,12,90}$=2*12*7=168mm <240mm

The above check also satisfies the conditions for the specimen which are sawed on an 45 degree angle, which are 170mm wide. Which is about equal to the minimum edge distance perpendicular to the grain.

Spacing and edge/end distances (see Figure 8.7)	Angle	Minimum spacing or edge/end distance
a_1 (parallel to grain)	$0^\circ \le \alpha \le 360^\circ$	$(3 + 2\lvert\cos\alpha\rvert)\,d$
a_2 (perpendicular to grain)	$0^\circ \le \alpha \le 360^\circ$	$3\,d$
$a_{3,t}$ (loaded end)	$-90^\circ \le \alpha \le 90^{0^\circ}$	max (7 d; 80 mm)
$a_{3,c}$ (unloaded end)	$90^{0^\circ} \le \alpha < 150^\circ$ $150^\circ \le \alpha < 210^\circ$ $210^\circ \le \alpha \le 270^\circ$	max($a_{3,t}\lvert\sin\alpha\rvert)\,d$; 3$d$) $3\,d$ max($a_{3,t}\lvert\sin\alpha\rvert)\,d$; 3$d$)
$a_{4,t}$ (loaded edge)	$0^\circ \le \alpha \le 180^\circ$	max([2 + 2 sin α) d; 3d)
$a_{4,c}$ (unloaded edge)	$180^\circ \le \alpha \le 360^\circ$	$3\,d$

Figure 53 Table 8.5 EC5[13] minimum spacing and edge and end distances for dowels

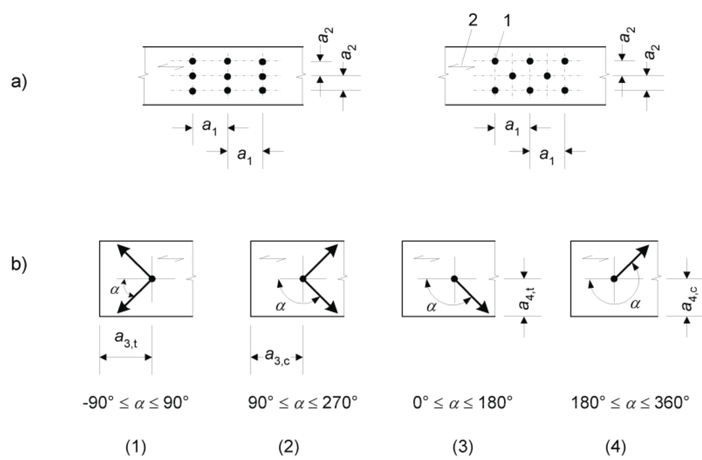


Figure 54 Edge distance and end distances according to EC5[13]

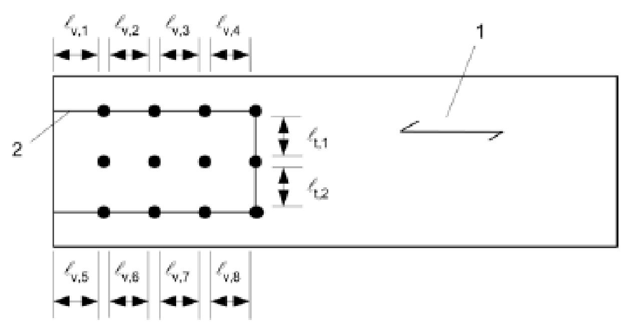
7.1.5 Shear timber

End distances used during experiments are:

- 84mm end distance for parallel to the grain specimen
- 60mm end distance for parallel to the grain specimen with reduced end distance
- 48mm end distance for perpendicular to the grain specimen
- 68mm end distance for specimen loaded on a 45 degrees angle

The shear resistance found in the product specification is 8.0N/mm^2. Through EC5 plug shear is calculated by the equation below.

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



Key:
1 Grain direction
2 Fracture line

Figure 55 EC5 shear failure[13]

$$A_{net,v} = \begin{cases} L_{net,v}\, t_1 & \text{failure modes (e, f, j/l, k, m)} \\ \dfrac{L_{net,v}}{2}\left(L_{net,t} + 2\, t_{ef}\right) & \text{all other failure modes} \end{cases} \qquad \text{(A.3)}$$

$$L_{net,v} = \sum_i l_{v,i}$$

$L_{net} = 2 \cdot (a_3 - 0.5\mathrm{d} + (n-1) \cdot a_1 - (\mathrm{n} - 1 \cdot \mathrm{d})$

$t_{ef} = \frac{F_{vd}}{f_{h \cdot d}} = \frac{36 \cdot 10^3}{108 \cdot 12} = 27.77mm$ for FM-II thickness 40mm

Number of dowels n (-)	Dowel diameter d (mm)	Spacing a_1 (mm)	End distance a3 (mm)	Thickness t or t_{ef} (mm)	EC5 L_{net} (mm)
1	12	60	84	20	156
2	12	60	84	20	252
3	12	60	84	20	348
1	12	60	60	20	108
2	12	60	60	20	204
3	12	60	60	20	300
1	12	60	48	20	84
2	12	60	48	20	180
3	12	60	48	20	276
1	12	60	68	20	124
1	12	60	84	27,77	156
2	12	60	84	27,77	252
3	12	60	84	27,77	348
2	12	60	48	27,77	180
3	12	60	48	27,77	276
1	12	60	68	27,77	124

table 12 L_{net} values of test specimen

End distance a3 (mm)	Number of dowels n (-)	EC5 L_{net} (mm)	Thickness t or t_{ef} (mm)	Dowel load per shear plane F_{vd} (kN)	Characteristic shear resistance Baubuche-Q f_v (N/mm^2)	Unity check shear capacity $\frac{F_{vd} \cdot n}{0.7L_{net} \cdot t \cdot f_v}$ (-)
84	1	156	20	25,92	8	1,48
84	2	252	20	25,92	8	1,84
84	3	348	20	25,92	8	2,00
60	1	108	20	25,92	8	2,14
60	2	204	20	25,92	8	2,27
60	3	300	20	25,92	8	2,31
48	1	84	20	25,92	8	2,76
48	2	180	20	25,92	8	2,57
48	3	276	20	25,92	8	2,52
68	1	124	20	25,92	8	1,87
84	1	156	27,77	36	8	1,48
84	2	252	27,77	36	8	1,84
84	3	348	27,77	36	8	2,00
48	2	180	27,77	36	8	2,57
48	3	276	27,77	36	8	2,52
68	1	124	27,77	36	8	1,87

table 13 Unity check shear resistance

A lot of specimen do not meet the shear resistance. What is interesting is that even single dowelled joints don't meet the requirements. This is odd considering that LVL-Q tested by Kobel failed ductile and not due to shear at all at a distance of 7d

7.1.6 Shear strength of past research

In the article of Kobel et al[2] confirmed that specimen D and G(Figure 56) failure at lower displacements due to plug shear. The maximum values of the embedment strength for these specimen have been noted in the table below.

d = 16 mm				
Configu-ration	$f_{h,\Delta=5mm}$ (EN 383)			
	l_3 [-]	n [-]	$f_{h,\Delta=5mm}$ [N/mm^2]	CoV [%]
C	7d	8	77	3.6
D	3.5d	7	72	3.9
Relative loss:			-6.5%	

d = 8 mm				
Configu-ration	$f_{h,\Delta=5mm}$ (EN 383)			
	l_3 [-]	n [-]	$f_{h,\Delta=5mm}$ [N/mm^2]	CoV [%]
F	7d	10	87	6.7
G	3.5d	5	81	2.6
Relative loss:			-7.3%	

Figure 56 Embedment strength at 5mm displacement and max displacement in tests Kobel[2]

The thickness of the timber for the specimen with dowel diameter 8 is 21mm and for dowel diameter 16, 49mm. From this the maximum load is calculated.

The mean values of the shear strength for the experiments of Kobel are the following. These are derived by F_{max} and the end distance as in Figure 55.

$$f_{v,8} = \frac{F_{\max}}{0.7 \cdot 2 \cdot L_{net,v} \cdot t} = \frac{f_h \cdot t \cdot d}{0.7 \cdot 2 \cdot (3.5d - 0.5d) \cdot t} = \frac{81 \cdot 21 \cdot 16}{0.7 \cdot 2 \cdot (3.5 \cdot 8 - 0.5 \cdot 8) \cdot 21} = 19.26 N / mm^2$$

$$f_{v,16} = \frac{F_{\max}}{0.7 \cdot 2 \cdot L_{net,v} \cdot t} = \frac{f_h \cdot t \cdot d}{0.7 \cdot 2 \cdot (3.5d - 0.5d) \cdot t} = \frac{72 \cdot 49 \cdot 16}{0.7 \cdot 2 \cdot (3.5 \cdot 16 - 0.5 \cdot 16) \cdot 49} = 17.14 N / mm^2$$

Both the maximum load and shear strength are a linearly dependent on the thickness and dowel diameter and thus two things are important the end distance/spacing and the ratio between embedment strength and shear strength. In the current setup with dowel diameter 12mm the dowels will fail and deform. In case of failure mode I this will not occur and the embedment strength will be even higher(around 100N/mm^2) this is though at larger deformations than 5mm.

Table 4 Embedment test results

Configuration	$f_{h,\Delta=5mm}$ (EN 383)			$f_{h,max}$			
	n [-]	$f_{h,\Delta=5mm}$ [N/mm^2]	CoV [%]	n [-]	$f_{h,max}$ [N/mm^2]	CoV [%]	$\Delta(F_{max})$ [mm]
B (d=20mm)	10	75	5.1	4	104	2.2	39
C (d=16mm)	8	77	3.6	4	100	5.0	21
E (d=12mm)	10	84	3.4	4	101	4.7	29
F (d=8mm)	10	87	6.7	5	101	4.8	16

Figure 57 Embedment strength test results Kobel[2]

Values found for shear were 19.26N/mm^2 and 17.14N/mm^2 for dowels 8mm and 16mm respectively. Hence a value is interpolated in between which is 18N/mm^2 because 12mm dowels are used.

$F_{bs,Rk} = 0.7 \cdot L_{net} \cdot \mathrm{t} \cdot f_{v,k} = 0.7 \cdot 156 \cdot 20 \cdot 18 = 39.3$kN for 1 dowel parallel to the grain
$F_{bs,Rk} = 0.7 \cdot L_{net} \cdot \mathrm{t} \cdot f_{v,k} = 0.7 \cdot 348 \cdot 20 \cdot 18 = 87.7$kN for 3 dowels parallel to the grain

End distance a3 (mm)	Number of dowels n (-)	Number of dowels n (-)	EC5 L_{net} (mm)	Thickness t or t_{ef} (mm)	Dowel load per shear plane F_{vd} (kN)	Interpolated shear resistance Kobel f_v (N/mm^2)	Unity check shear capacity $\frac{F_{vd} \cdot n}{0.7 L_{net} \cdot t \cdot f_v}$ (-)
84	1	1	156	20	25,92	18	0,66
84	2	2	252	20	25,92	18	0,82
84	3	3	348	20	25,92	18	0,89
60	1	1	108	20	25,92	18	0,95
60	2	2	204	20	25,92	18	1,01
60	3	3	300	20	25,92	18	1,03
48	1	1	84	20	25,92	18	1,22
48	2	2	180	20	25,92	18	1,14
48	3	3	276	20	25,92	18	1,12
68	1	1	124	20	25,92	18	0,83
84	1	1	156	27,77	36	18	0,66
84	2	2	252	27,77	36	18	0,82
84	3	3	348	27,77	36	18	0,89
48	2	2	180	27,77	36	18	1,14
48	3	3	276	27,77	36	18	1,12
68	1	1	124	27,77	36	18	0,83

table 14 Shear resistance according to values Kobel

This is a rather high estimation of the shear resistance thus shear failures at some point is not unlikely.

7.2 Verifying strength of steel

Material factors are not taken into account as extreme maximum values for loads have been taken.

7.2.1 Steel fasteners and plate

Calculation failure mode steel plate and steel connectors when transferring loads from test equipment.

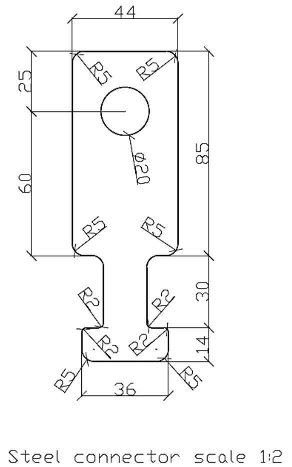


Figure 58 Dimensions steel connector

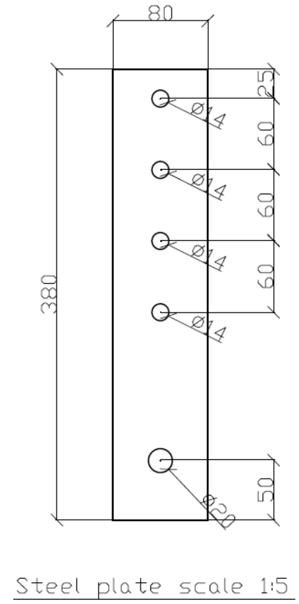
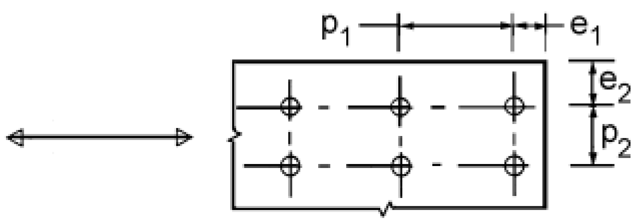


Figure 59 Dimensions steel plate



	Steel quality	t(mm)	w(mm)	e_1(mm)	e_2(mm)	f_y(mm)	f_u(mm)
Steel connectors	S355	12	44	25	22	355	510
Steel plate	S355	12	80	50	40	355	510

table 15 Properties steel plate and connector

	Steel quality	d_n(mm)	d_0(mm)	A(mm^2)	f_y(N/mm^2)	f_{ub}(N/mm^2)
Steel connectors	10.9	20	20	314	900	1000

table 16 Properties steel bolts 10.9

Embedment resistance(table 3.4 EN1993-1-8)

$$F_{b,Rd} = \frac{k_1 \alpha_b f_u d t}{\gamma_{M2}}$$

$\alpha_b = \min\left(\alpha_d; \frac{f_{ub}}{f_u}; 1{,}0\right)$
$k_1 = \min\left(1.4\frac{p_2}{d_0} - 1.7; 2{,}5\right)$
$\alpha_d = \frac{e_1}{3d_0}$

	$\alpha_d = \frac{e_1}{3d_0}$	$\frac{f_{ub}}{f_u}$	$1.4\frac{p_2}{d_0} - 1.7$	k_1	α_b
Steel connectors	0.42	1.96	-	2.5	0.42
Steel plate	0.82	1.96	-	2.5	0.82

table 17 Embedment values steel plate and connector

Shear resistance bolt(table 3.4 EN1993-1-8)

$$F_{v,Rd} = \frac{\alpha_v \ f_{ub} \ A}{\gamma_{M2}}$$

With:
α_v=0.5 for class 10.9
Shear resistance plate(eq. 6.18 EN1993-1-1)

$$V_{pl,Rd} = \frac{A_v(f_y/\sqrt{3})}{\gamma_{M0}}$$

With:
$A_v = 2(e_1 - 0.5 \cdot d) \cdot t$
Tensile resistance (eq. 6.6 EN1993-1-1)

$$N_{pl,Rd} = \frac{A f_y}{\gamma_{M0}}$$

$A = (w -\cdot d) \cdot t$
F_{ed} has been determined by the maximum of 6 shear planes of the dowels times the maximum force 36kN (see table 8).

Failure mode	Formula	F_r(kN)	F_{ed}(kN)	Unity check (n=4 for connectors)
Embedment resistance connector	$F_{b,Rd} = \frac{k_1 \alpha_b f_u d t}{\gamma_{M2}}$	254	216	0.85
Embedment resistance plate	$F_{b,Rd} = \frac{k_1 \alpha_b f_u d t}{\gamma_{M2}}$	125.8	216	0.43
Shear resistance bolt	$F_{v,Rd} = \frac{\alpha_v \ f_{ub} \ A}{\gamma_{M2}}$	157	216	0.69
Shear resistance connector	$V_{pl,Rd} = \frac{A_v (f_y / \sqrt{3})}{\gamma_{M0}}$	73.8kN	216	0.73
Shear resistance plate	$V_{pl,Rd} = \frac{A_v (f_y / \sqrt{3})}{\gamma_{M0}}$	196kN	216	1.12
Tensile resistance connector	$N_{pl,Rd} = \frac{A f_y}{\gamma_{M0}}$	102.2kN	216	0.53
Tensile resistance plate	$N_{pl,Rd} = \frac{A f_y}{\gamma_{M0}}$	255.6kN	216	0.85

table 18 Unity check steel plate and connectors

One unity check does not meet, however calculations are with characteristic values. Also steel is generally significantly stronger than described in product specifications. Since there are only 2 out of the 60 experiments capable of reaching this height and even then this is not that likely. Therefor the risk will be taken that the steel plate is strong enough to hold for all experiments.

7.2.2 Steel plate and bolts

Calculation failure mode steel plate when transferring forces from bolts to timber.

	Steel quality	t(mm)	w(mm)	e_1(mm)	e_2(mm)	f_y(mm)	f_u(mm)
Steel plate	S355	12	80	25	40	355	510

table 19 Properties steel plate

	Steel quality	d_n(mm)	d_0(mm)	A(mm^2)	f_y(N/mm^2)	f_{ub}(N/mm^2)
Bolt 12:9	12.9	12	14	113	1080	1200

table 20 Properties bolts

	$\alpha_d = \frac{e_1}{3d_0}$	$\frac{f_{ub}}{f_u}$	$1.4\frac{p_2}{d_0} - 1.7$	k_1	α_b
Steel plate	0.42	2.35	-	2.5	0.42

table 21 Embedment factors steel plate

F_{ed} has been determined by the maximum force for 2 dowelled shear planes which is 72(36x2 see table 8)

Failure mode	Formula	F_r(kN)	F_{ed}(kN)	Unity check
Embedment resistance plate	$F_{b,Rd} = \frac{k_1 \alpha_b f_u d t}{\gamma_{M2}}$	77.1	72	0.93
Shear resistance bolt	$F_{v,Rd} = \frac{\alpha_v f_{ub} A}{\gamma_{M2}}$	142	72	0.51
Shear resistance plate	$V_{pl,Rd} = \frac{A_v (f_y / \sqrt{3})}{\gamma_{M0}}$	196	72	0.37
Tensile resistance connector	$N_{pl,Rd} = \frac{A f_y}{\gamma_{M0}}$	93.5	72	0.77
Tensile resistance plate	$N_{pl,Rd} = \frac{A f_y}{\gamma_{M0}}$	289.7	72	0.25

table 22 Unity check steel plate and bolts

8 Summary of tests results

This paragraph first shows the numerical results of the test specimen and further discusses observations made. In the next paragraph an analysis is made on the important subjects.

During tests some of the tests have been stopped before reaching failure as the deformation was so large that continuing the tests was deemed unnecessary. The individual results and pictures of all tests can be found in the appendix, here any notable things are listed and graphs are presented.

For coding of the test specimen see paragraph 4.6.2 Coding. Some points are listed below for understanding the way experiments are coded:

- Series with T20 have a thickness of 20mm and are designed to fail in failure mode I.
- Series with T40 have a thickness of 40mm and are designed to fail in failure mode II.
- Series with N1R, N2R or N3R, are tests with shorter end distances than the EC5 recommends.
- In a later stage of testing series were added with an extra “S” T20_A0_N1_1S at the end of the coding. This included tests which clamped together at the top see Figure 60. The nuts were adjusted “hand tight”(literally) no wrench involved.

Figure 60 Strengthened denoted with an S at the end of coding

This paragraph first shows a table of the test results. During the experiments it became quite clear that the shear strength was a lot higher than was noted in the product specifications. The values resembled the values found during the experiments were Kobel. The shear strength mentioned in the product specification of Baubuche is most likely noted lower due to the possibility of rolling shear. Thus using the values given by Baubuche leads to very conservative results.

8.1 Overview of load carrying capacity tests

Test series	n_{tests} (-)	n_{dowels} (-)	ρ_m (kg/m^3)	$\sigma_{\rho m}$ (kg/m^3)	$COV_{\rho m}$ (%)	MOC (%)	F_{max} Aver. (kN)	F_{max} σ (kN)	F_{max} COV (%)	F_{5mm} Aver. (kN)	F_{5mm} σ (kN)	F_{5mm} COV (%)	F_{max} per dowel (kN)
T20_A0_N1	5	1	783	14,94	1,91	5,12	49,05	2,95	6,01	45,80	4,57	9,99	49,05
T20_A0_N1_S	3	1	792	8,38	1,06	5,12	62,47	1,91	3,05	52,31	2,85	5,46	62,47
T20_A0_N2	5	2	784	14,65	1,87	5,36	97,33	5,08	5,22	92,36	4,64	5,02	48,67
T20_A0_N3	5	3	786	13,56	1,72	5,52	137,76	3,02	2,19	134,15	1,05	0,78	45,92
T20_A0_N1R	5	1	788	13,15	1,67	5,88	48,29	1,93	4,00	46,07	1,97	4,28	48,29
T20_A0_N1R_S	3	1	796	7,24	0,91	5,88	55,47	5,19	9,36	50,20	4,17	8,31	55,47
T20_A0_N2R	5	2	790	13,93	1,76	5,88	96,74	4,78	4,94	92,49	4,63	5,00	48,37
T20_A0_N3R_S	5	3	792	15,07	1,90	6,04	139,04	16,01	11,52	141,63	5,83	4,12	46,35
T20_A45_N1	3	1	793	23,73	2,99	5,63	51,57	2,82	5,47	42,43	1,07	2,51	51,57
T20_A90_N1	5	1	779	12,08	1,55	4,62	45,41	3,43	7,56	41,26	3,14	7,62	45,41
T20_A90_N2	5	2	782	10,27	1,31	5,16	83,08	4,65	5,59	76,54	7,58	9,91	41,54
T20_A90_N3	2	3	773	2,77	0,36	5,31	117,95	7,37	6,25	-	-	-	39,32
T20_A90_N3_S	3	3	791	7,86	0,99	5,31	119,76	5,13	4,29	-	-	-	39,92
T40_A0_N1	2	1	810	7,20	0,89	5,73	65,73	2,83	4,31	54,34	0,61	1,11	65,73
T40_A0_N2	2	2	814	7,23	0,89	6,05	113,21	1,41	1,25	104,22	3,67	3,52	56,60
T40_A0_N3	2	3	818	9,26	1,13	5,90	164,60	0,36	0,22	160,18	2,00	1,25	54,87
T40_A90_N1	2	1	808	2,95	0,37	6,12	53,57	0,28	0,53	48,98	0,23	0,46	53,57
T40_A90_N2	2	2	812	6,32	0,78	5,88	107,61	9,25	8,59	96,33	1,20	1,24	53,80
T40_A90_N3	2	3	814	8,46	1,04	6,01	142,91	14,90	10,43	147,17	0,56	0,38	47,64

σ=standard deviation
ρ_m=mean density

Values of K_s(embedment stiffness) are not derived but can be calculated based on the values found in the tests

On the next page the embedmentstrength is given for the test specimen. Note that f_h for specimen with thickness 40mm is not entirely accurate. It is difficult to calculate the exact embedmentstrength for specimen as it is dependent on width b and f_h which are both unknown in FM-II. Underneath the principle Is shown for using a distance b to calculate the embedmentstrength in FM-II.

Embedmentstrength of test results is calculated by(with n=number of dowels):

$$f_h = \frac{F_{\max\ or\ 5mm}}{n * d * t} \quad for\ FM-I$$

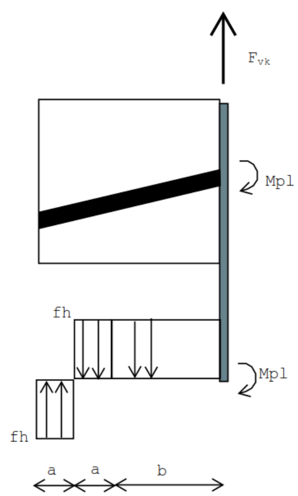
$$f_h = \frac{F_{\max\ or\ 5mm}}{n * d * b} \quad for\ FM-II\ with\ b = 36.5mm\ parallel\ and\ b = 38.5mm\ perpendicular\ to\ the\ grain$$

Failure mode FM-II

F_{vk}=2(b*f_h*d) (factor 2 for double shear plane)

Because both b and f_h are unknown and are dependent on each other it is impossible to accurately calculate the embedmentstrength with the current measurements.

Thus a simplification is made Failure II is to occur at b=t(thus failure in mode I or at a minimum of t=b1 as illustrated to the right.



With
f_h=embedmentstrength
d= dowel diameter
F_{vk}=Shear strength

Failure mode FM-III

Equilibrium of moment around steel plate

$$2M_{pl} = f_h * d * \frac{b_1^2}{2}$$

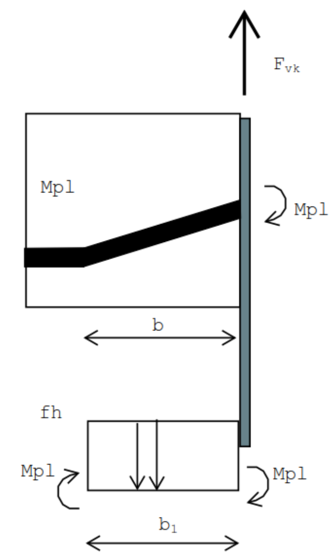
$$b_1 = 2\sqrt{\frac{M_{pl}}{f_h * d}}$$

$$M_{pl} = \frac{1}{6} * f_y * d^3$$

$$M_{pl} = \frac{1}{6} * 1327N/mm^2 * 12mm^3 = 0.382kNm$$

$b_1 = 2\sqrt{\frac{0.382kNm}{95.4*12}}$ =36.5mm for dowels loaded parallel to the grain

$b_1 = 2\sqrt{\frac{0.382kNm}{86*12}}$ =38.5mm for dowels loaded perpendicular to the grain



Mean embedmentstrength $f_{h,5mm}$ of specimen T20_A0_N1 and T20_A90_N1 have been used to calculate b_1. Which 95.4 N/mm^2 and 86.0 N/mm^2 respectively.

f_y=yield strength steel (mean result 1327N/mm^2 from tensile tests dowels see table 24)

Note that with experiments failing in FM-II the gap between the steel plate increased. This results in a loss of shear capacity, and thus also results in lower embedment strength in this calculation. Which is not the case in reality, only internal lever arm becomes larger and thus results into a lower F_{vk}.

Test series	Numer of tests (-)	f_{hFmax} (N/mm²)	COV (-)	f_{h5mm} (N/mm²)	COV (-)	comments
T20_A0_N1	5	102,2	6,01	95,4	9,99	
T20_A0_N1_S	3	130,1	3,05	109,0	5,46	
T20_A0_N2	5	101,4	5,22	96,2	5,02	
T20_A0_N3	5	95,7	2,19	93,2	0,78	
T20_A0_N1R	5	100,6	4,00	96,0	4,28	
T20_A0_N1R_S	3	115,6	9,36	104,6	8,31	
T20_A0_N2R	5	100,8	4,94	96,3	5,00	
T20_A0_N3R_S	5	96,6	11,52	98,4	4,12	
T20_A45_N1	3	107,4	5,47	88,4	2,51	
T20_A90_N1	5	94,6	7,56	86,0	7,62	
T20_A90_N2	5	86,5	5,59	79,7	9,91	
T20_A90_N3	2	81,9	6,25	-	-	
T20_A90_N3_S	3	83,2	4,29	-	-	
T40_A0_N1	2	75,0	4,31	62,0	1,11	*
T40_A0_N2	2	64,6	1,25	59,5	3,52	**
T40_A0_N3	2	62,6	0,22	61,0	1,25	**
T40_A90_N1	2	58,0	0,53	53,0	0,46	***
T40_A90_N2	2	58,2	8,59	52,1	1,24	***
T40_A90_N3	2	51,6	10,43	53,1	0,38	***

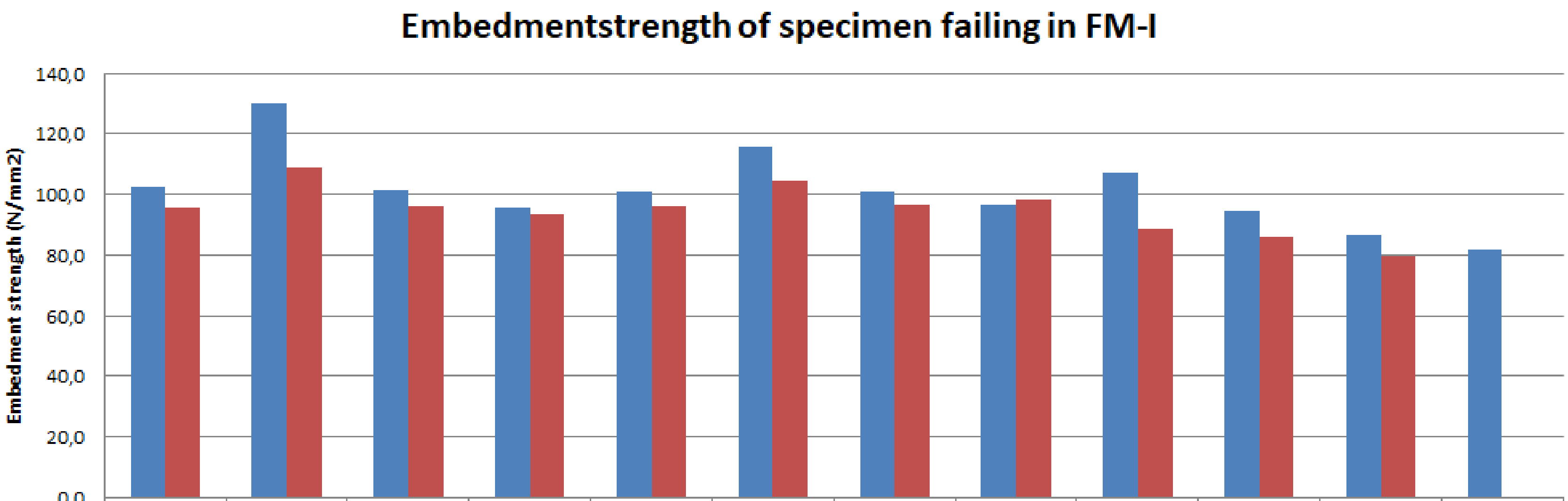
table 23 Results embedmentstrength(see previous page for calculations of embedmentstrength)

f_{hFmax}=Embedmentstrength according to en383; f_{h5mm}=embedmentstrength at 5mm displacement(same as used by Kobel) to account for that sawn timber is brittle and the en 383 has been created for primarily sawn timber.

* test series showed a gap

** test series showed a gap but also started to shear the top layers adjacent to the steel plate

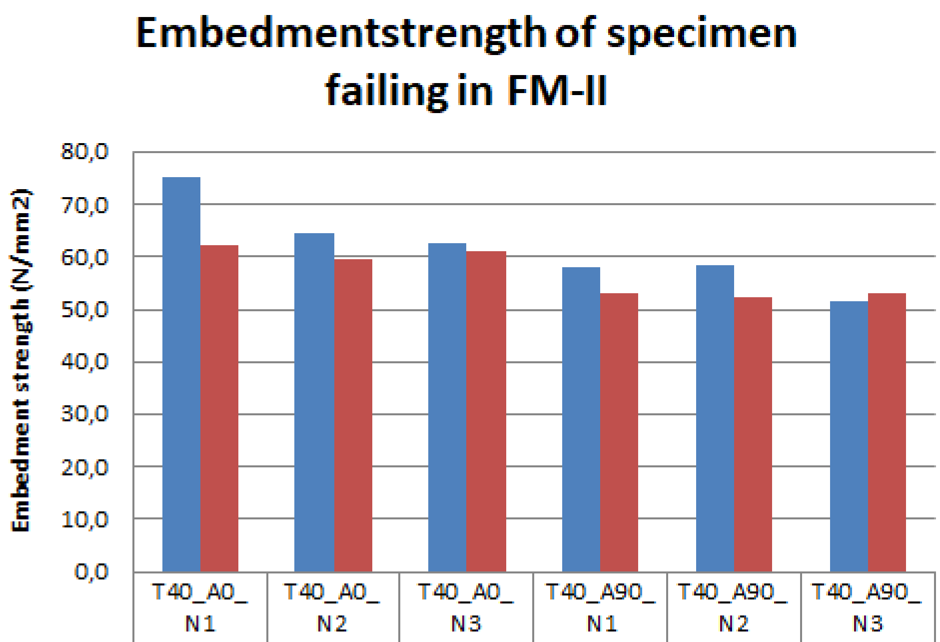
*** Test series showed a gap and failed due to failure/bending at net cross section



	T20_A0_N1	T20_A0_N1_S	T20_A0_N2	T20_A0_N3	T20_A0_N1R	T20_A0_N1R_S	T20_A0_N2R	T20_A0_N3R_S	T20_A45_N1	T20_A90_N1	T20_A90_N2	T20_A90_N3
fhFmax	102,2	130,1	101,4	95,7	100,6	115,6	100,8	96,6	107,4	94,6	86,5	81,9
fh5mm	95,4	109,0	96,2	93,2	96,0	104,6	96,3	98,4	88,4	86,0	79,7	0,0

Figure 61 Embedment strength in specimen failing in FM-I

Note these are actually connection tests and not embedment tests, but the results found in FM-I and in that of embedment tests should be very similar.



	T40_A0_N1	T40_A0_N2	T40_A0_N3	T40_A90_N1	T40_A90_N2	T40_A90_N3
fhFmax	75,0	64,6	62,6	58,0	58,2	51,6
fh5mm	62,0	59,5	61,0	53,0	52,1	53,1

Figure 62 Embedmentstrength in specimen failing in FM-II

Note these are actually connection tests and not embedment tests the embedment strength found in above graph is not representing the real embedment strength well, this due to failing in FM-II. see start paragraph 8.1 on how this was calculated

8.2 *Tests Parallel to the grain*

8.2.1 T20_A0_N1,2,3

Single dowelled tests parallel to the grain resulted in Failure mode as it was designed for. The specimen failed very ductile and were halted after a sufficient amount of deformation(at 15-20mm). At larger deformation the timber was pushed out of plane and against the steel plate. But a relatively plastic strength was reached at 49kN.

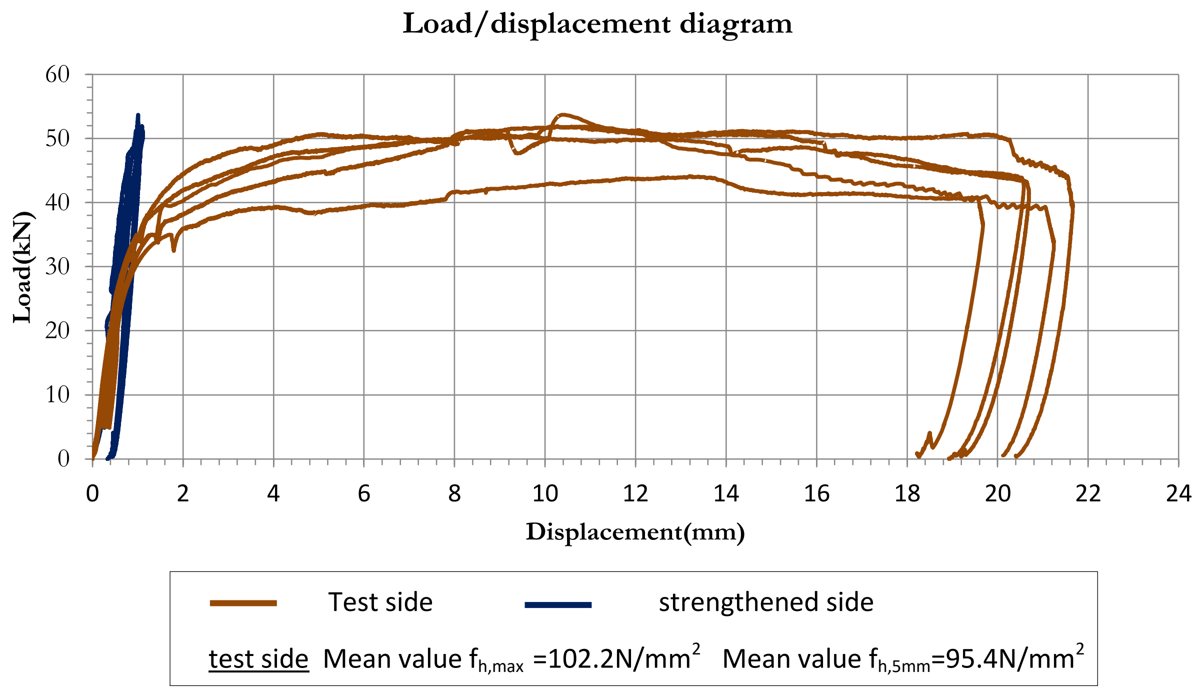


Figure 63 Load displacement diagram of experiments T20_A0_N1

Figure 64 Embedment failure in test specimen T20_A0_N1

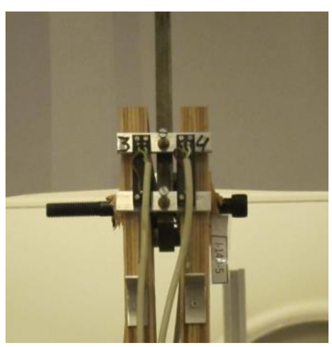


Figure 65 Closeup during testing specimen T20_A0_N1_4

Figure 66 minor deformations found in dowels

For the experiments with two dowels, 2 out of the 5 experiments failed due to tensile failure, while the other 3 failed due to embedment/shear failure. The tensile failure in the experiments were unexpected, the net cross section was expected to fail at approximately 122.4kN(characteristic tensile strength). Failure which occurred at 97 kN was most likely induced to stress concentrations near the dowel the failure occurred after around 8-10mm of displacement which was at a relatively large displacement. Experiments that did not end up in tensile failure failed to a combination of shear and embedment failure. For these specimen shear occurred between the dowels. This could be either a sort of plug shear or block shear.(Figure 70 and Figure 71). For block shear this occurred at the transition from parallel veneer to cross veneer.

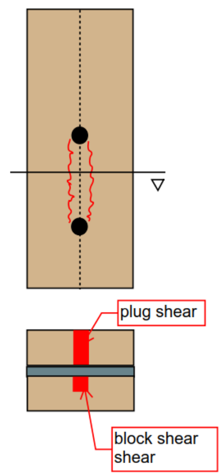


Figure 67 Schematic view of plug shear or block shear between the dowels(see Figure 70 and Figure 71 for pictures of experiments)

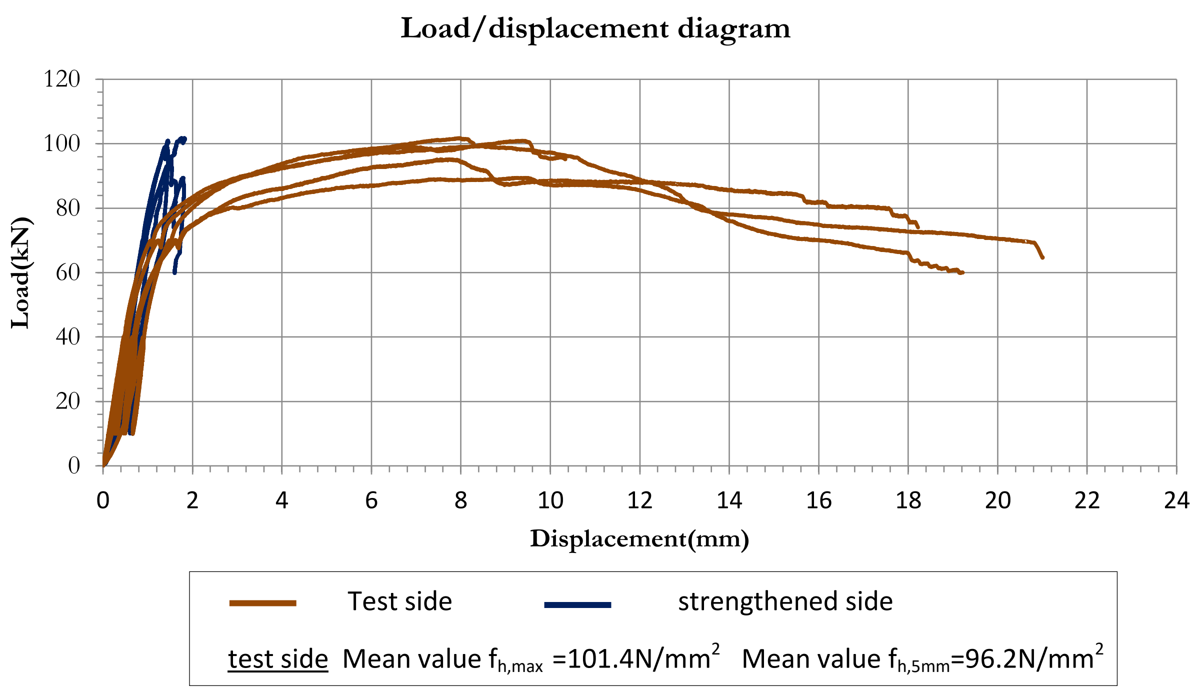


Figure 68 Load displacement diagram of experiments T20_A0_N2

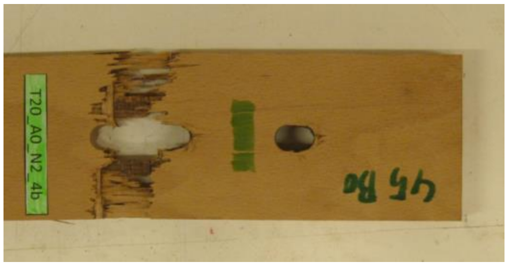


Figure 69 Tensile failure

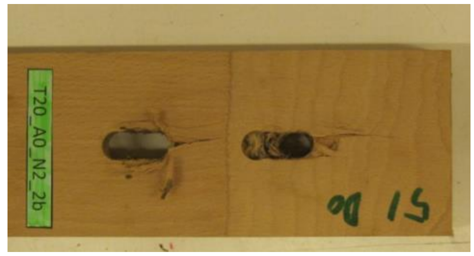


Figure 70 Partial shear between dowels

Figure 71 Full shear between dowels

For the experiments with 3 dowels, 4 out of 5 experiments failed due to tensile failure while the other failed due to a mix of both shear and embedment. Failure occurred at 137kN which was significantly higher than with 2 dowels. This failure however occurred at a much earlier displacement than for experiments with two dowels. These experiments seemed to fail at their "normal" tensile capacity while the experiments with 2 dowels suffered from high peak stresses resulting in earlier tensile failure.

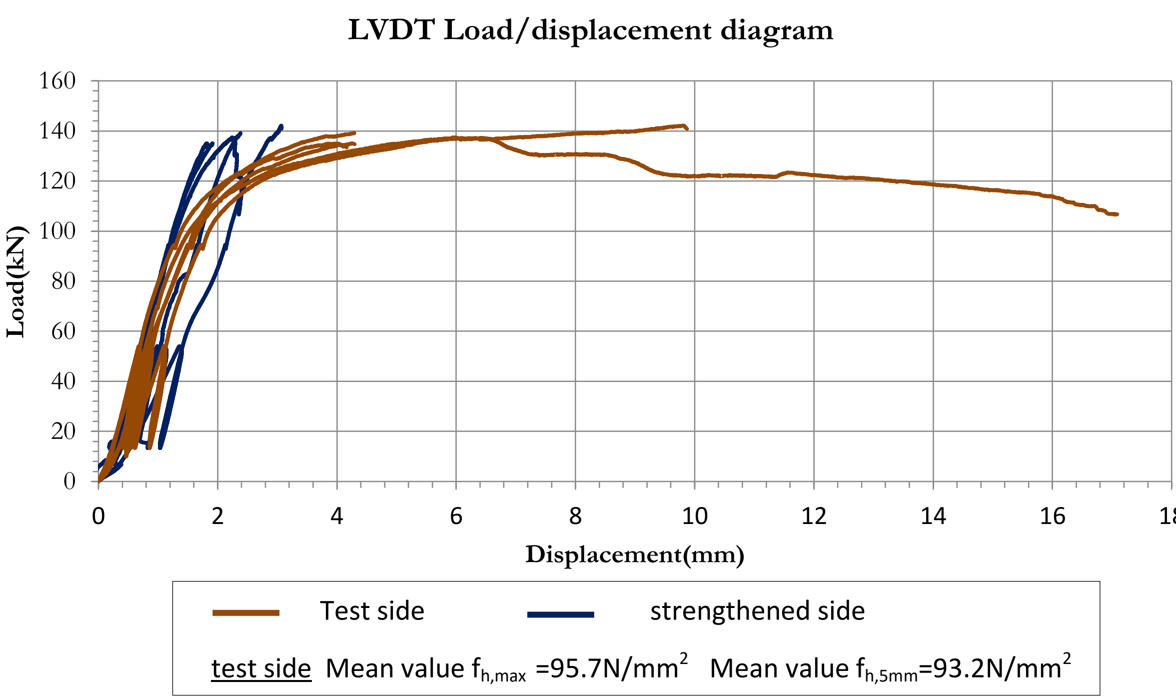


Figure 72 Load displacement diagram of experiments T20_A0_N3

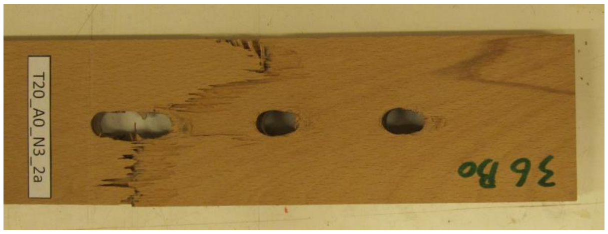


Figure 73 tensile failure

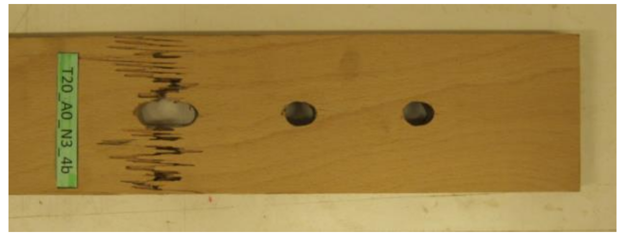


Figure 74 tensile failure

8.2.2 T20_A0_N1R,2R,3R

These tests were very similar to the tests T20_A0_N1, however with reduced end distances. The load reached was about the same and due to statistical variance even a little bit higher than tests with an higher end distance. While tests with 7d end distance didn't result in any shear failure, the tests with an end distance of 5d started to fail due to shear at a distance of around 10-14mm. Thus an end distance of around 6d seems to be the breaking point between shear failure or a full embedment failure.

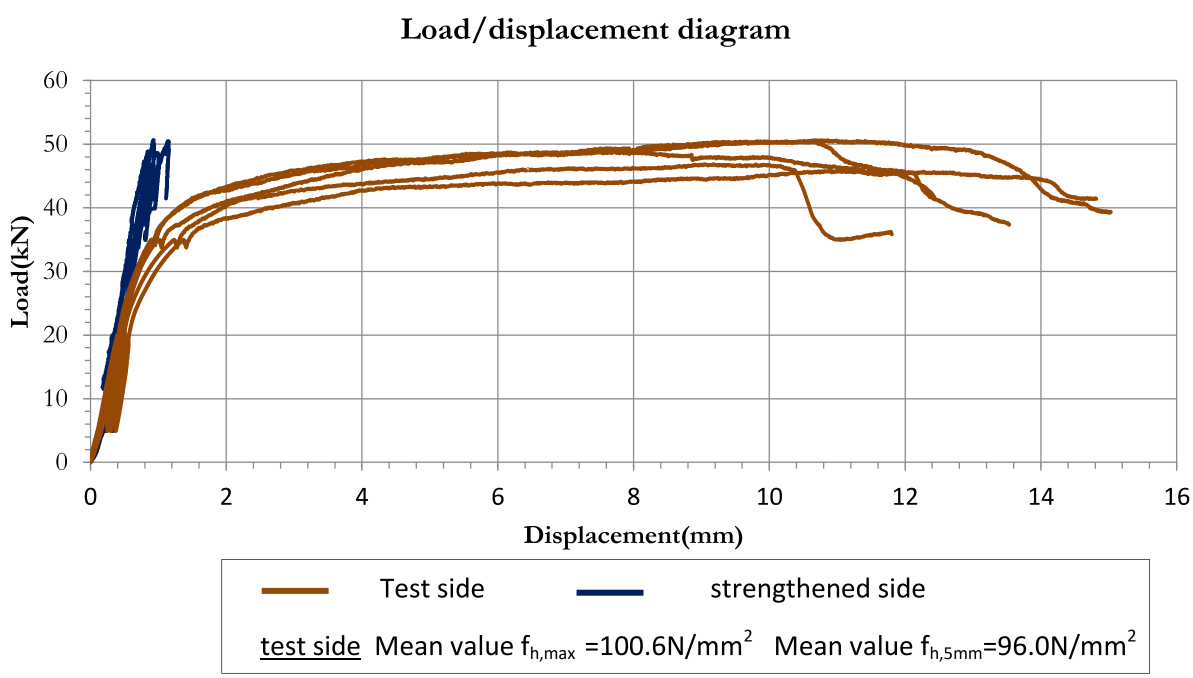


Figure 75 Load displacement diagram of experiments T20_A0_N1R

Figure 76 shear failure

Figure 77 shear failure

Failure in specimen with 2 dowels varied. The following failures were observed. The load carrying capacity and the ductility remained fairly similar to that of T20_A0_N2.

- 3 shear failures
- 1 splitting failure
- 1 tensile failures

The failures were however similar tensile failure at the net cross section. Shear failure between the dowels or at the end distance. Just as with an end distance of 7d the tensile failure occurred at 100kN which was earlier than expected. During the tests also 1 splitting failure was observed this splitting failure was the only splitting failure that occurred over all tests so this test seemed to be an anomaly.

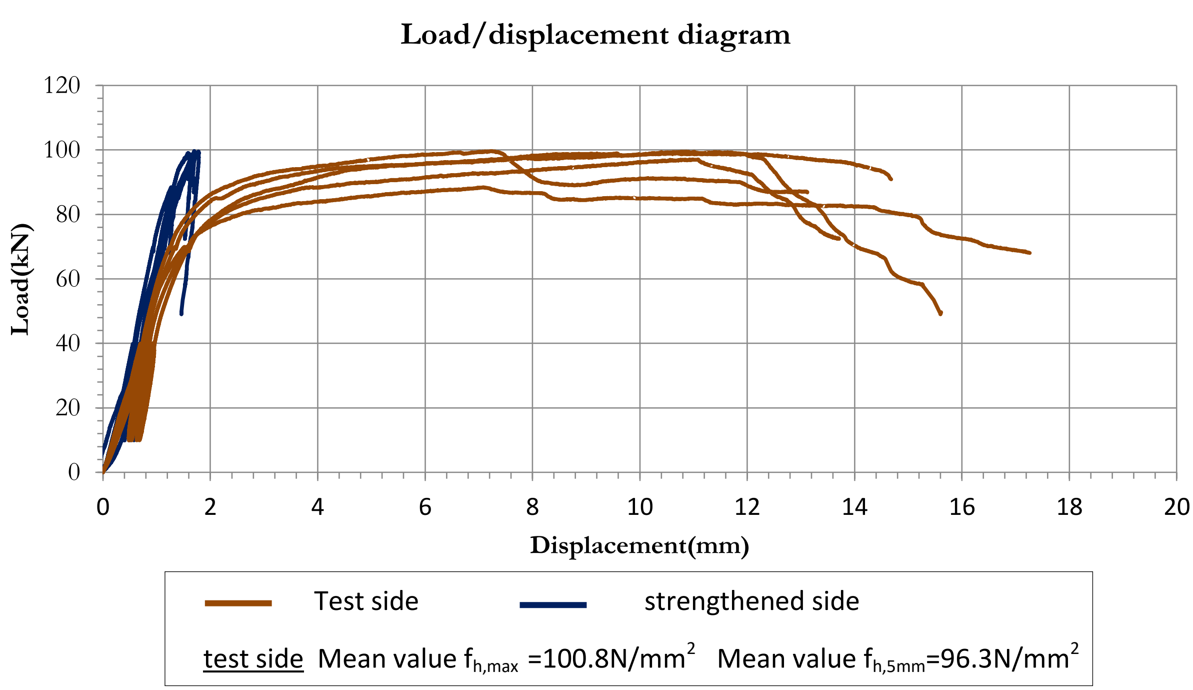


Figure 78 Load displacement diagram of experiments T20_A0_N2R

Figure 79 test 1 shear failure

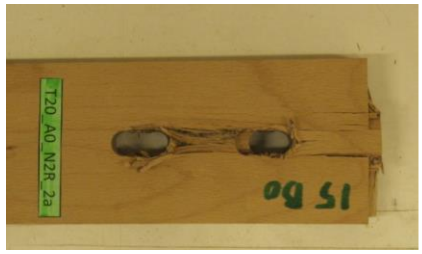


Figure 80 test 2 shear failure

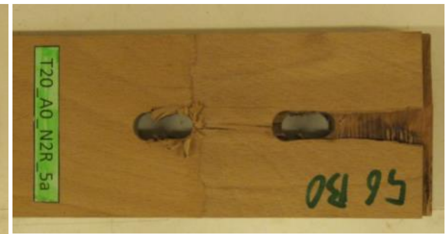


Figure 81tensile failure

Figure 82 test 3 tensile failure

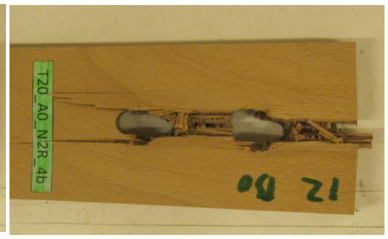


Figure 83 splitting failure

Failure at the net-cross section has always occurred at For this reason the specimen have been strengthened at the test side as the test resulted were expected to be similar to that of T20_A0_N3(see figure below). It was expected that the clamping the ends of the timber together would have no effect on failure mode I or tensile failure.

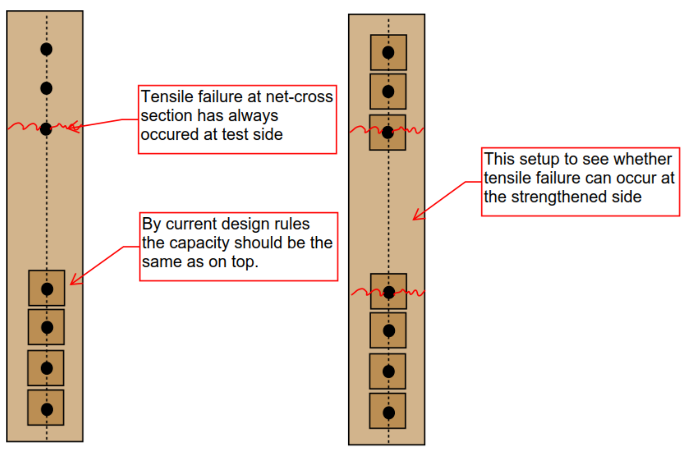


Figure 84 Impression tensile failure occurring in experiments

The failures that occurred were:

- 4 times tensile failure on test side
- 1 time failure on strengthened side

Due to all specimen failing in tensile failure and not due to shear or any failure. It turned out that clamping the test specimen together affected that load carrying capacity of the connection. As in this case failure occurred once at the strengthened side.

Figure 85 both sided clamped together during testing

Figure 86 tensile failure at test side

Figure 87 tensile failure at strengthened side

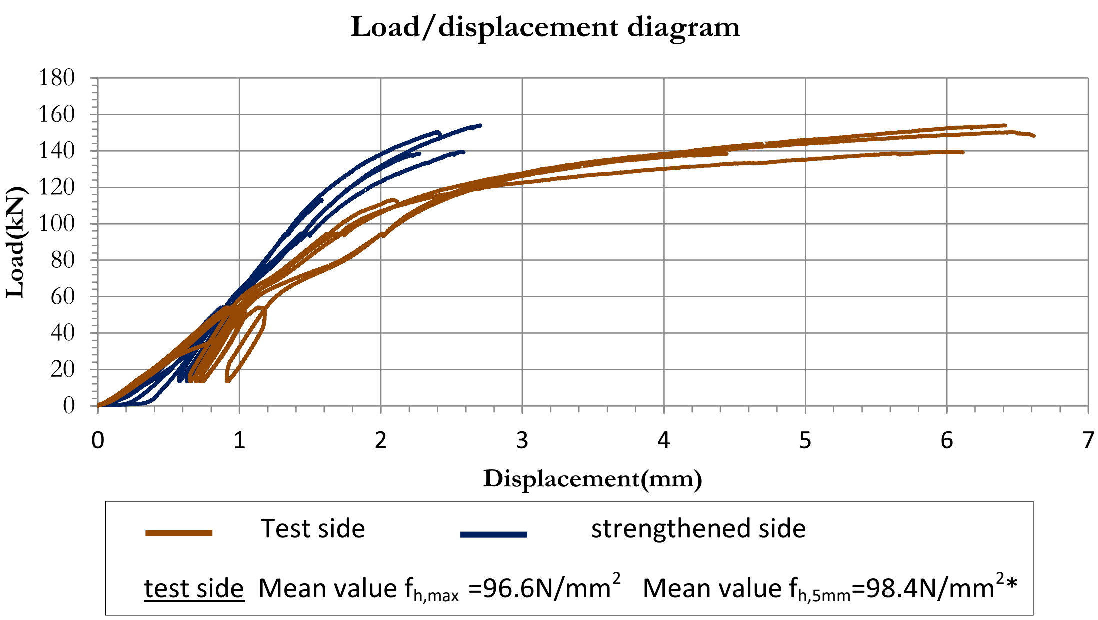


Figure 88 Load displacement diagram of experiments T20_A0_N3R_S

**Values of f_{hmax} and f_{5mm} are a bit odd, but this has to do with averaging the values. 2/5 experiments failed before 5mm, which results into f_{hmax} consisting out of 5 different values and f_{h5mm} out of 3.*

8.2.3 T20_A0_N1_S and T20_A0_N1R_S

During testing with specimen T20_A0_N3R_S some affects were believed to be present due to clamping together of the specimen. The tests shown remarkable results. The results of clamping the test specimen resulted in a strength increase to multiple parameters

- Increased shear resistance
- Increased embedment strength

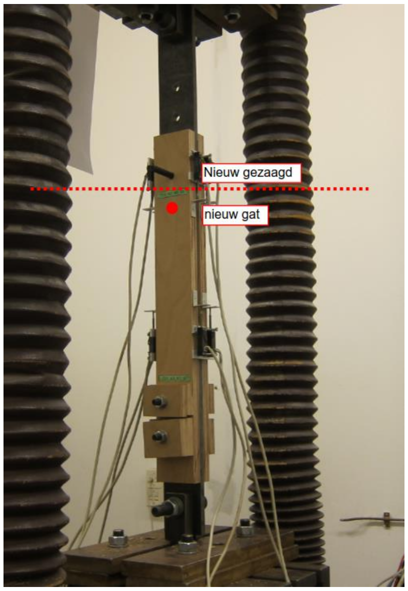


Figure 89 Clamping specimen together


Figure 90 “new” specimen

The increase in embedment strength almost certainly comes from densification of timber behind the dowel. Earlier test specimen allowed crushed timber behind the dowel to move out of plane. The clamped specimen restricted this and resulted in a higher embedment strength.

The shear strength was also likely to be increased due to this effect. But the reason why this was as much affected is less clear than for embedment strength.

The holes of the strengthened side were used twice leading to more hole clearance in the timber, which also shows from the curves. The holes on the test side were redrilled in shortened specimen of T20_A0_N1 and T20_A0_N1R.

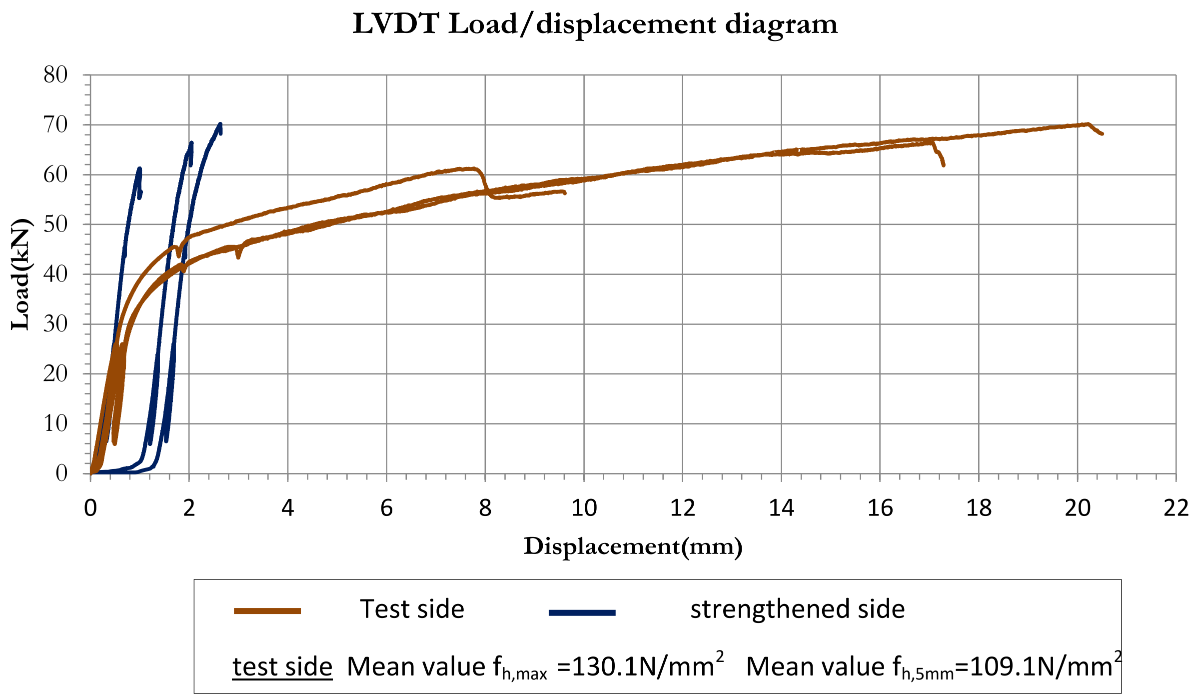


Figure 91 Load displacement diagram of experiments T20_A0_N1_S

The strengthened side reacts a bit strange this is due to the dowel holes already being used once for earlier experiments.

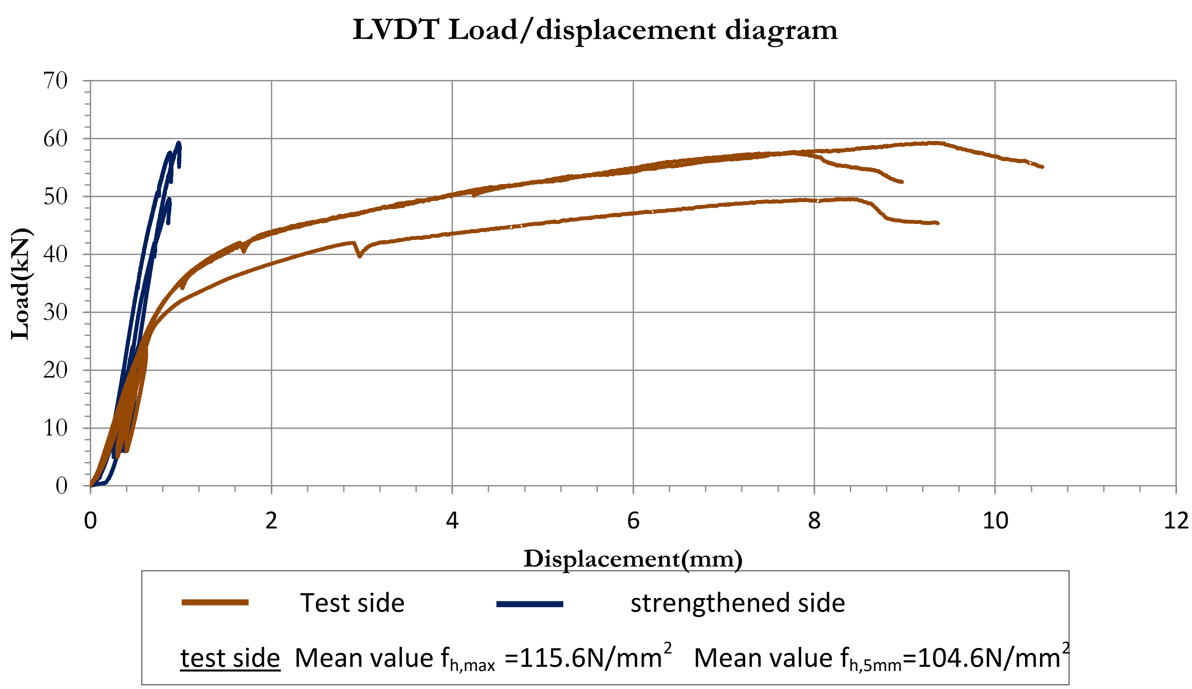


Figure 92 Load displacement diagram of experiments T20_A0_N1R_S

Figure 93 densification with 5d end distance

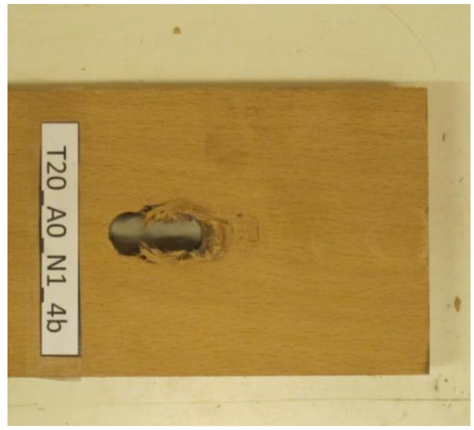


Figure 94 densification with 7d end distance

Figure 95 defect in the timber causing 1 veneer to shear out

Figure 96 Anomaly, 1 veneer sheared out

8.2.4 T40_A0_N1,2,3

Tests were done with minimum end distances by EC5. The thickness of 40mm has a lower level of cross-layers which resulted in FM-II as was designed. Although only 2 experiments each where done the results seemed almost identical for all series of tests with a thickness of 40mm. Strength was expected to be around 60 kN. But reached 52 kN at about 5mm of displacement and nearly up to 60-70kN at large displacements.

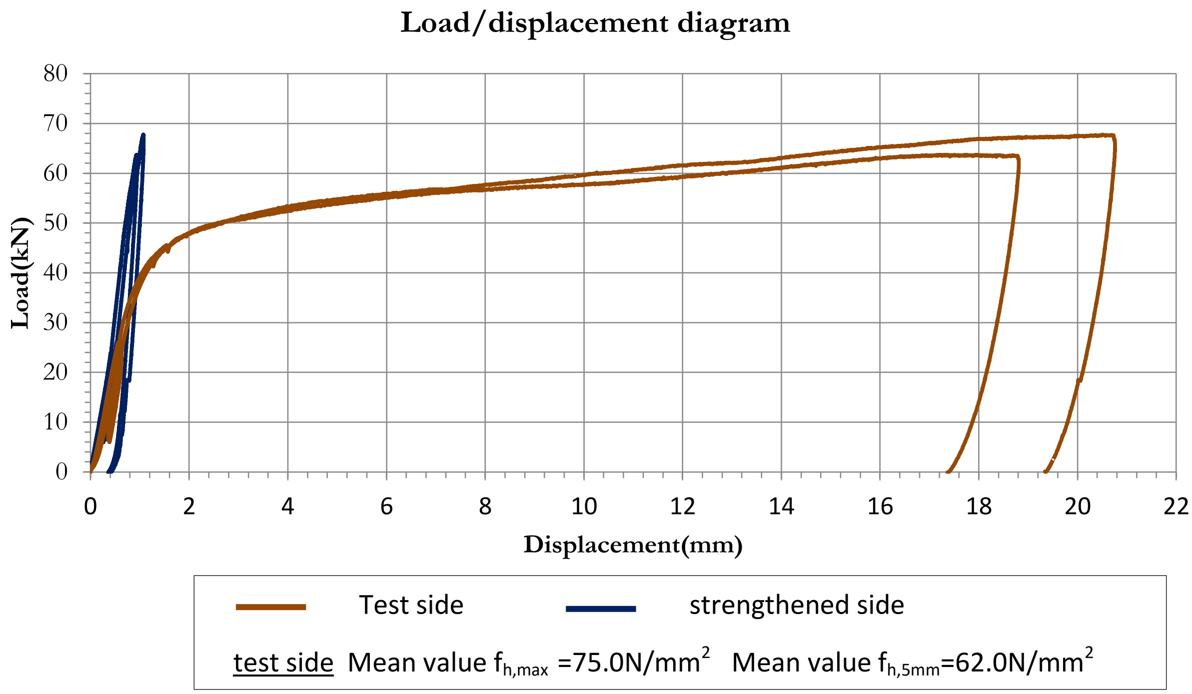


Figure 97 Load displacement diagram of experiments T40_A0_N1

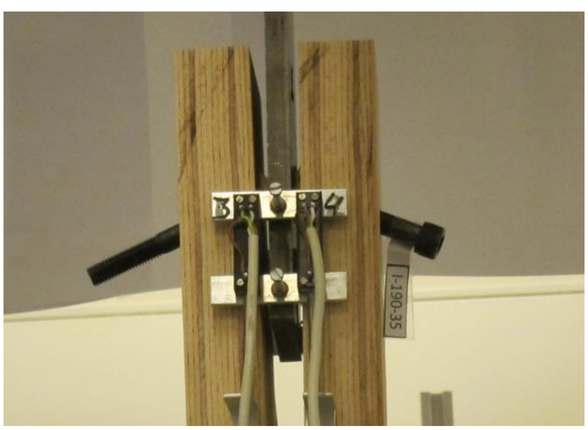


Figure 98 Failure mode II in experiments T40_A0_N1

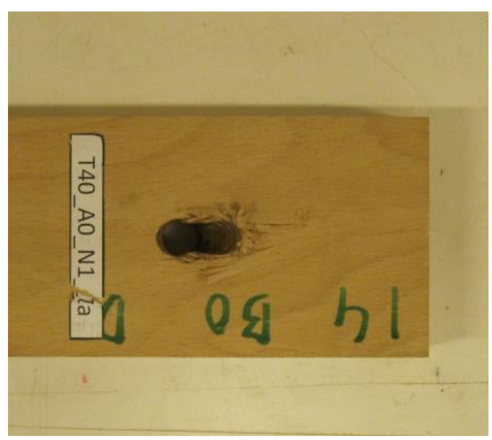


Figure 99 embedment failure in test specimen

The experiments with 2 or 3 dowels seemed to fail in similar fashion with the exception that shear failure occurred each time between the dowels. This failure was also observed earlier in experiments with T20_A0_N1 and seems to be a reoccurring pattern. The spacing of 5d seems to be too minimal.

Figure 100 failure mode II in experiments T40_A0_N2

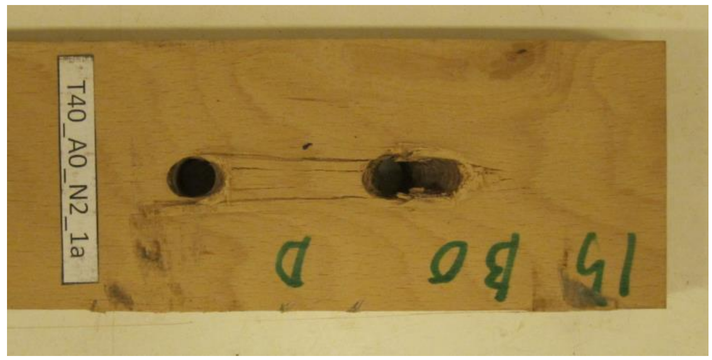


Figure 101 shear between the dowels in experiments T40_A0_N2

Figure 102 Failure mode II in experiments T40_A0_N3

Figure 103 shear between the dowels in experiments T40_A0_N3

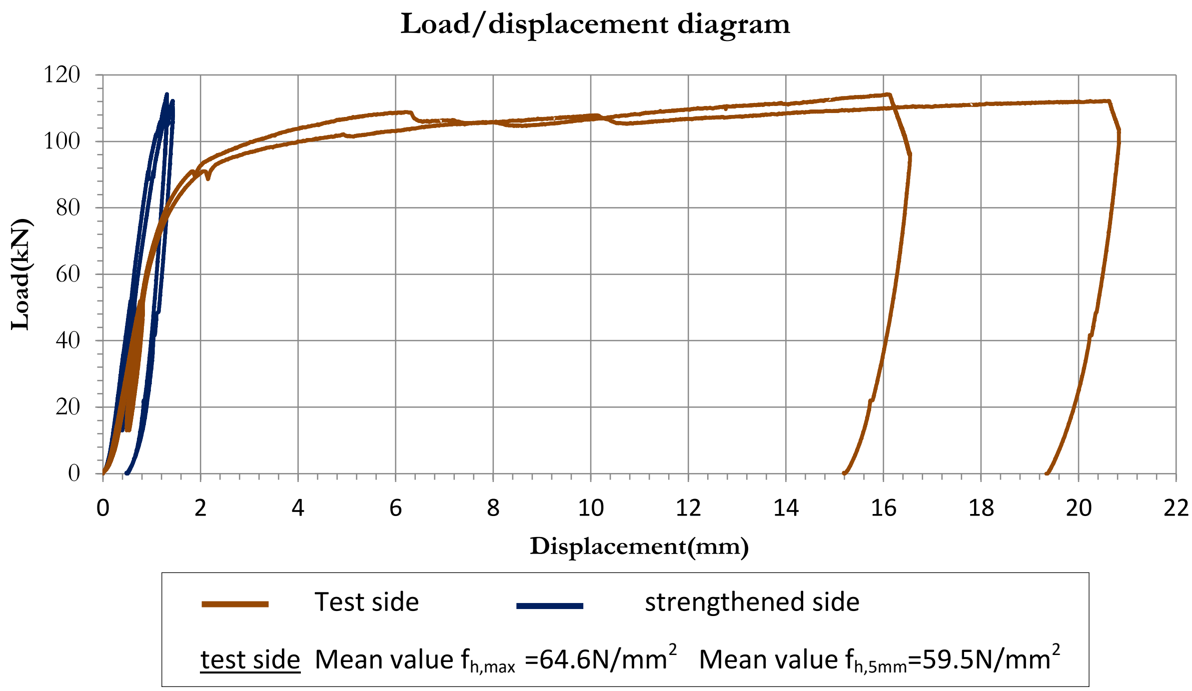


Figure 104 Load displacement diagram of experiments T40_A0_N2

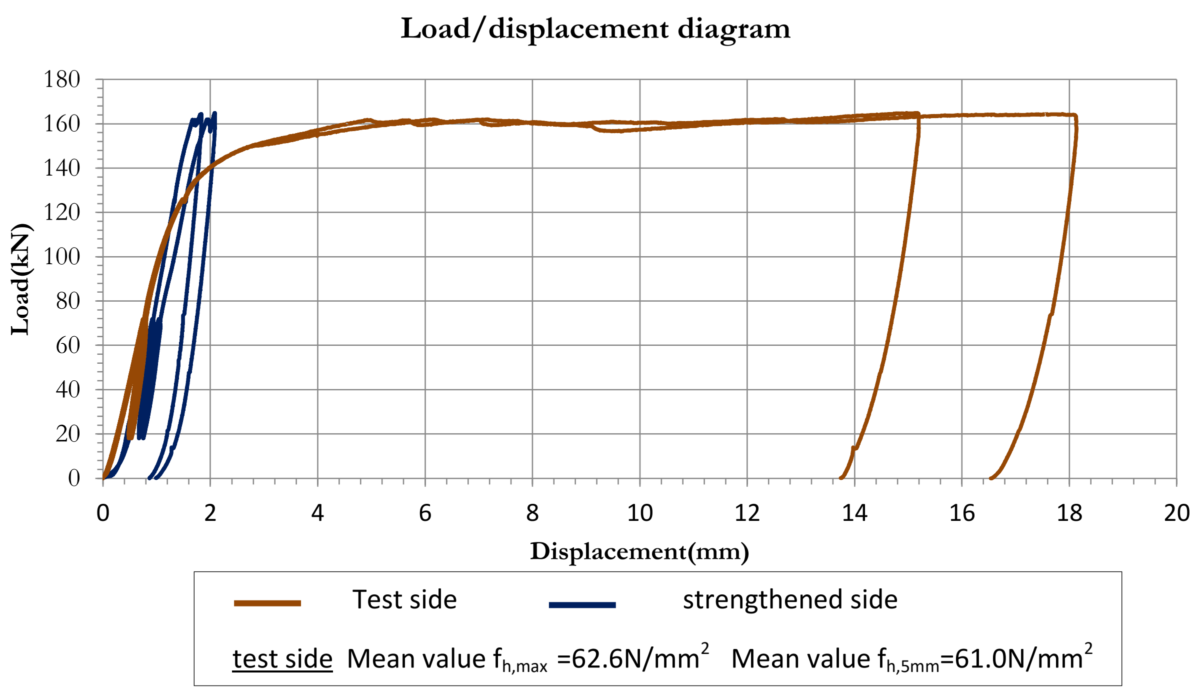


Figure 105 Load displacement diagram of experiments T40_A0_N3

8.3 Tests perpendicular to the grain

8.3.1 T20_A90_N1,2,3

Singled dowelled tests loaded perpendicular to the grain showed high load capacity but lower than loaded perpendicular to the grain. All specimen ended up in shear failure at some points which led to a reduction of capacity. The failure shear failure however was not as brittle as for loaded parallel to the grain.

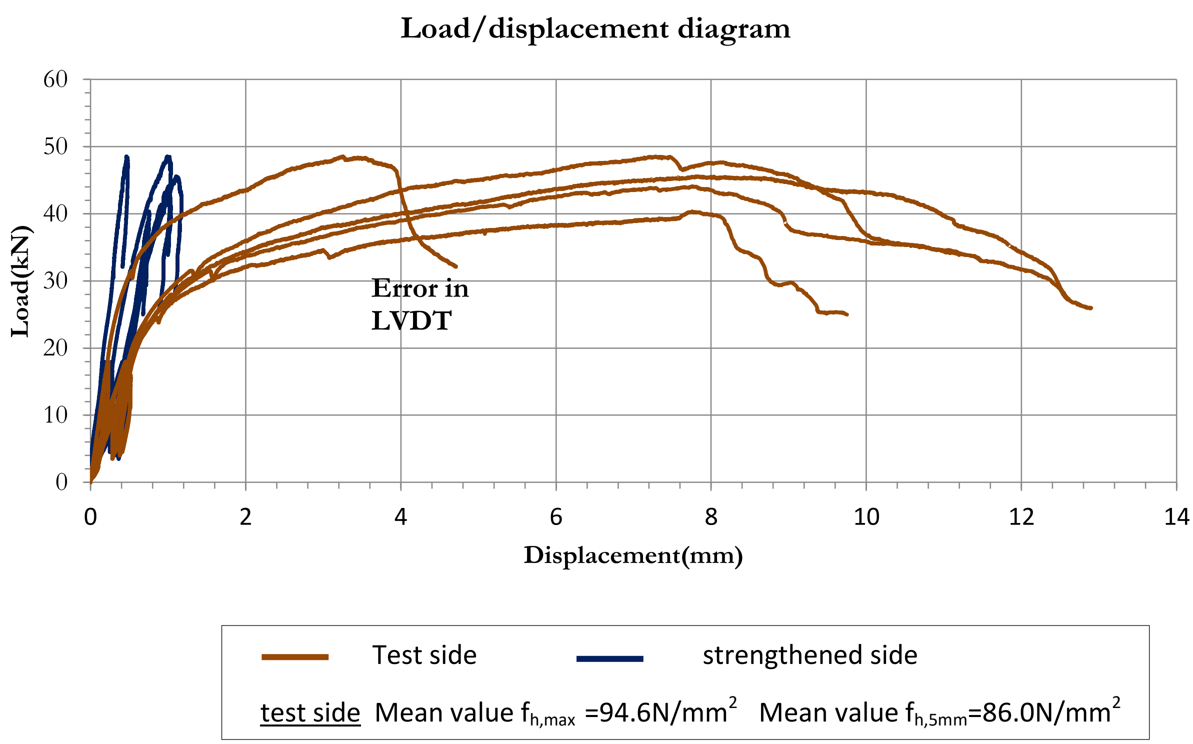


Figure 106 Load displacement diagram of T20_A90_N1

Figure 107 Shear failure in specimen T20_A90_N1_2b

Tests with 2 or 3 dowels all failed due to tensile failure. This was at a significantly lower tensile strength than was expected. This is likely caused by shear stresses or because the forces are not evenly distributed along the net cross section. The effective width at which the cross section can distribute the tensile stress is also likely to be the cause of the early tensile failure.

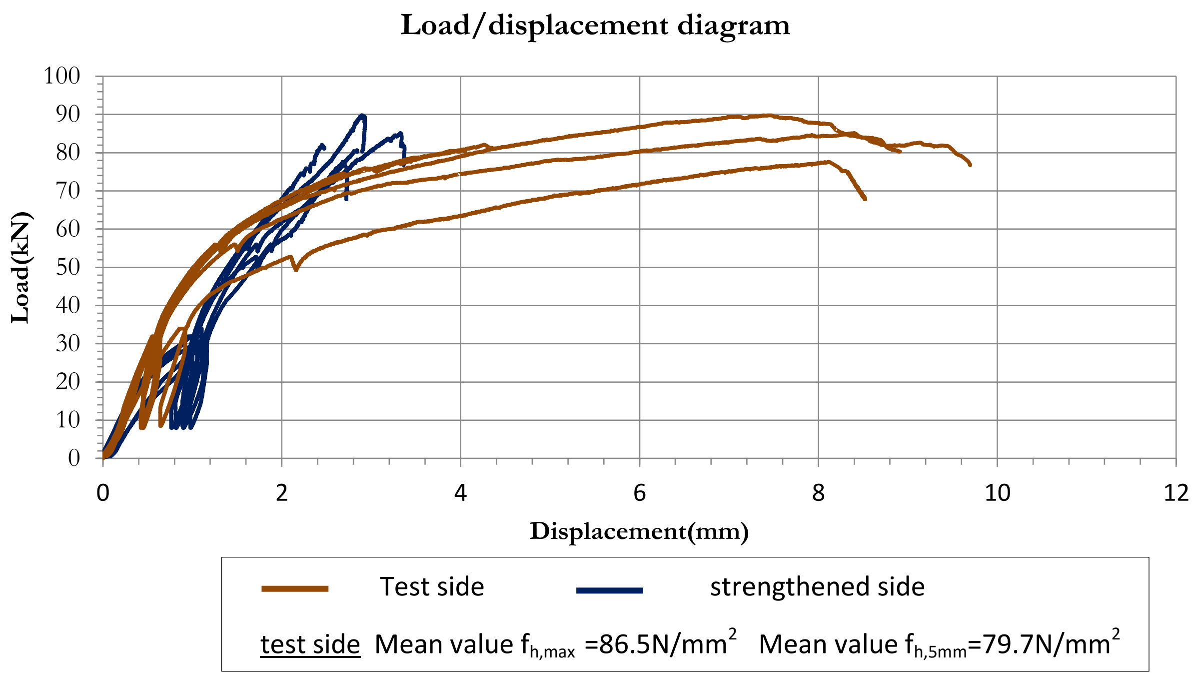


Figure 108 Load displacement diagram of T20_A90_N2

As with the experiments parallel to the grain 2 dowelled specimen failed on a lower tensile load than those with 3 dowels. This seems to confirm that the peak stresses near the dowel cause an early tensile failure. 3 out of 5 tests with 3 dowelled connections were clamped together at the top side. This however seemed to have no effects on the end results.

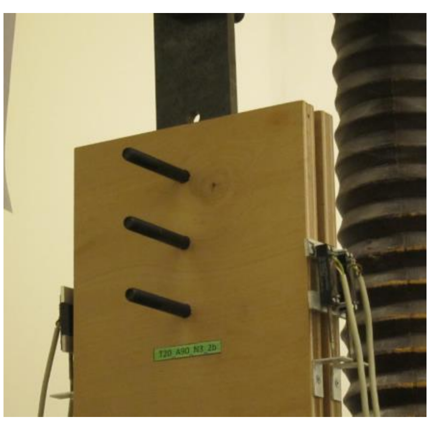


Figure 109 T20_A90_N3_1,2

Figure 110 T20_A90_N3_3,4,5 clamped together at test side

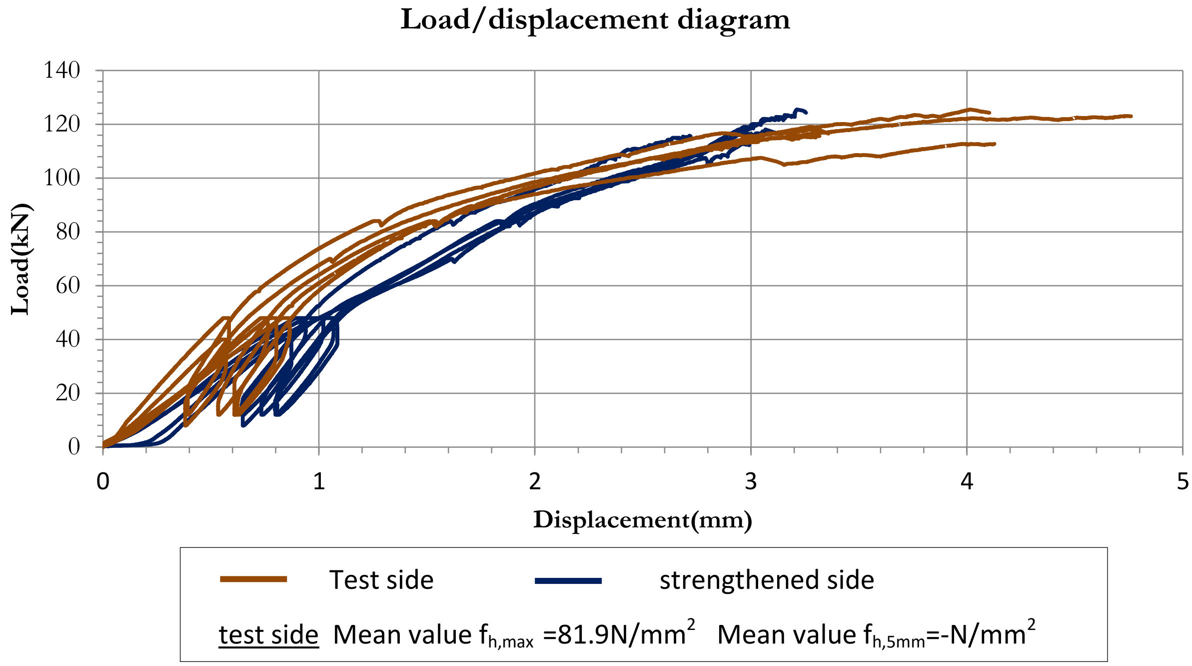


Figure 111 Load displacement diagram of T20_A90_N3

Figure 112 Tensile failure in T20_A90_N2

Figure 113 Tensile failure in T20_A90_N3

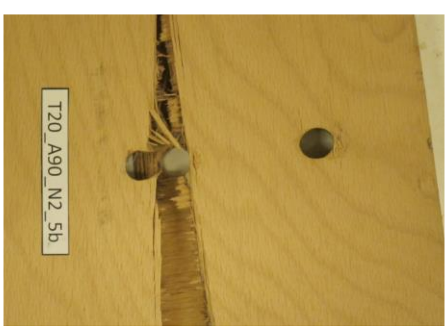


Figure 114 Tensile failure in T20_A90_N2

Figure 115 Tensile failure in T20_A90_N3

8.3.2 T40_A90_N1,2,3

The one dowelled specimen failed due embedment failure/dowel plastification. Unlike the experiments that failed in FM-I no shear was observed. This is likely due to the shear force being lower relative to the thickness(due to FM-II).

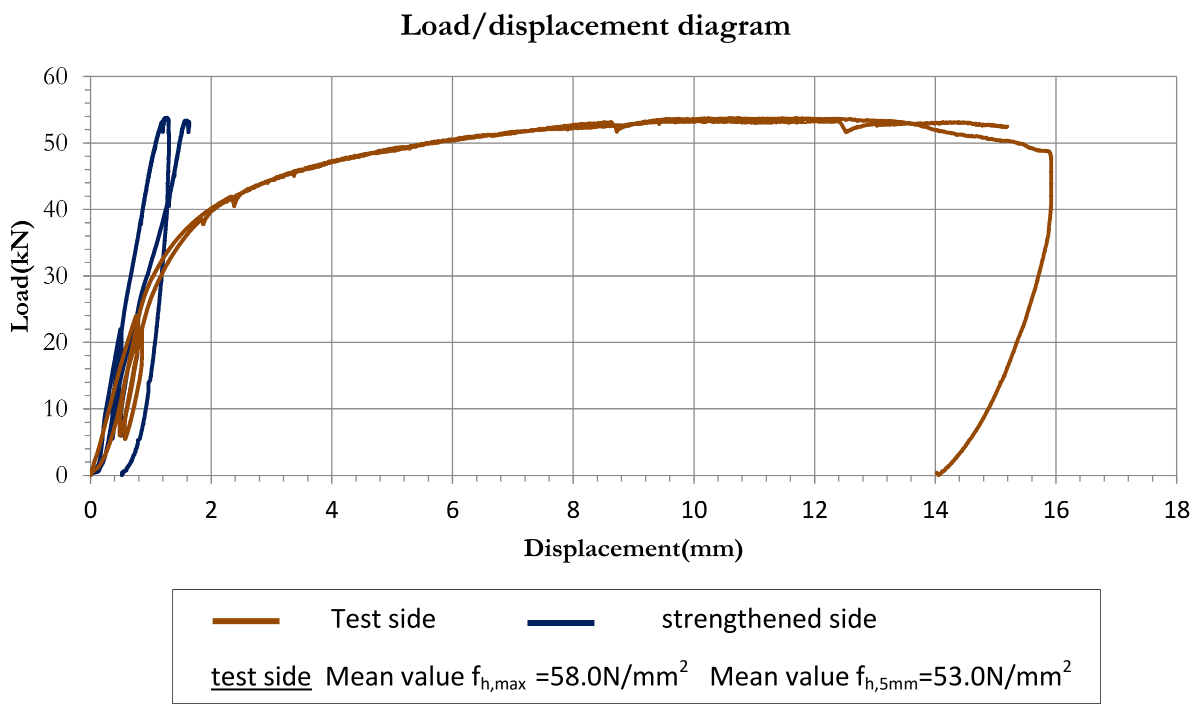


Figure 116 Load displacement diagram of experiments T40_A90_N1

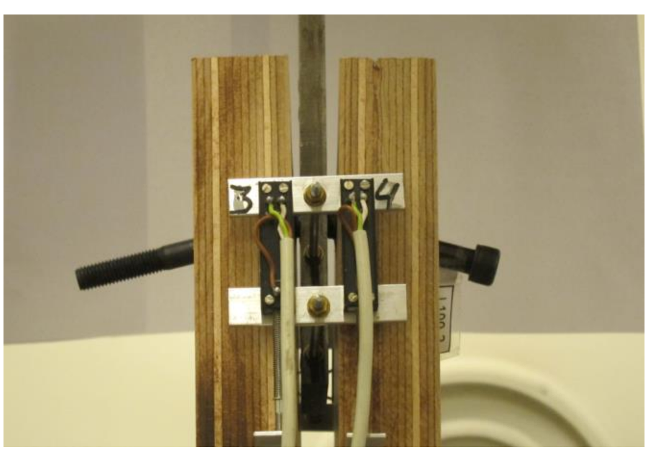


Figure 117 Failure mode II in experiments T40_A90_N1

Figure 118 Failure mode II in experiments T40_A90_N1

Experiments with 2 or 3 dowels failed in a bending/tensile failure. Due to timber slipping off the dowels the timber was pushed sideways resulting in a bending failure instead of a tensile failure. This occurred for all specimen with 2 or 3 dowels. The overall strength was higher for 3 dowels though.

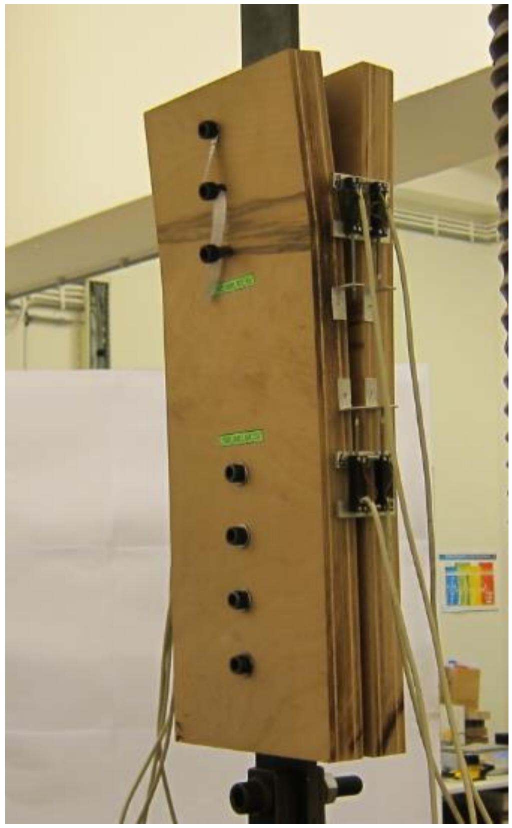


Figure 119 Bending/tensile failure in experiments T40_A90_N3(Also happened for T40_A90_N2)

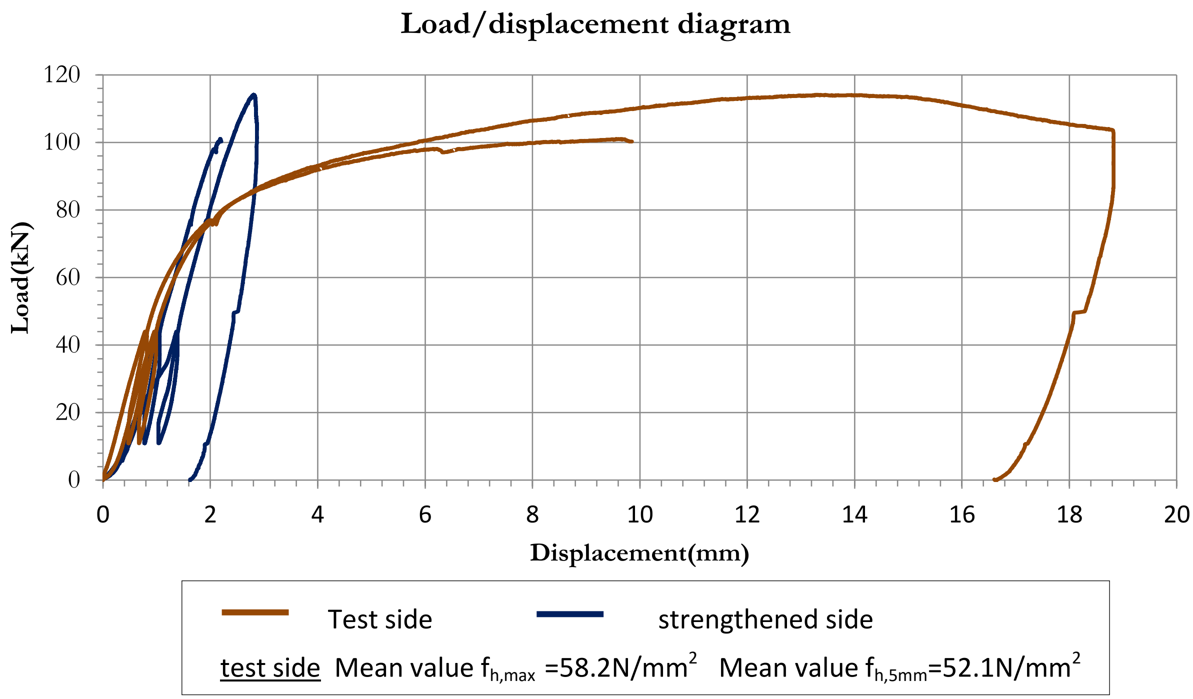


Figure 120 Load displacement diagram of experiments T40_A90_N2

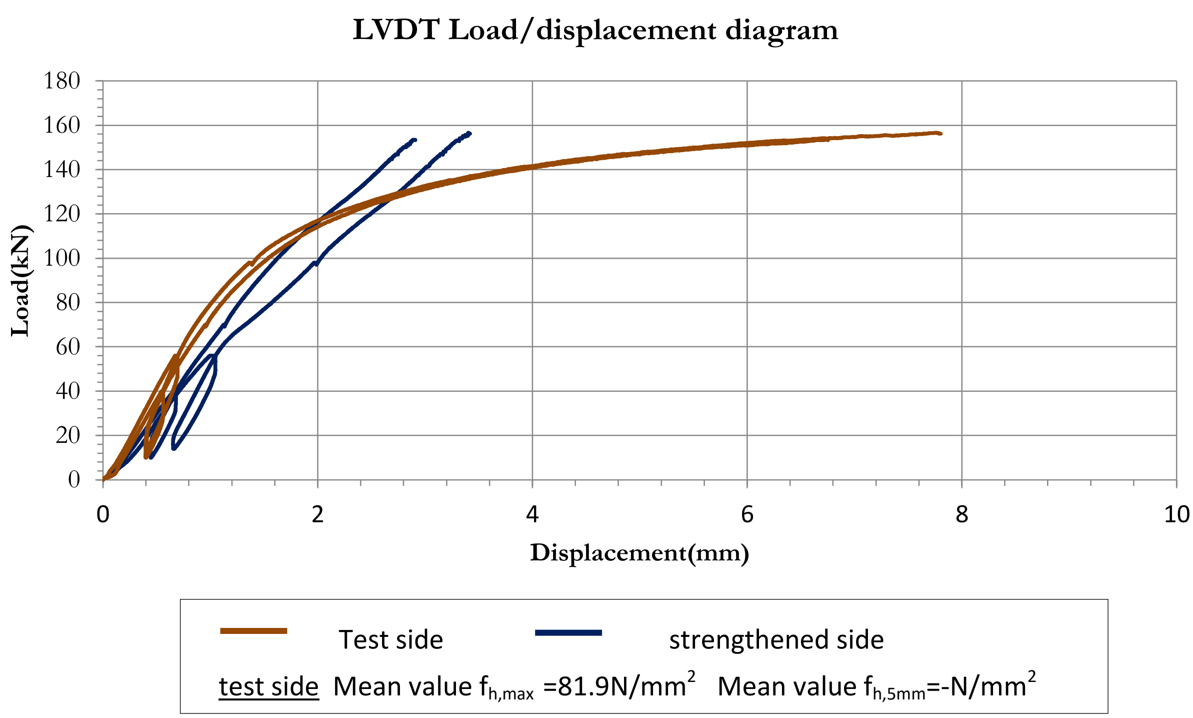


Figure 121 Load displacement diagram of experiments T40_A90_N3

8.4 Tests at 45° to the grain

Embedment failure was found in all specimen. The specimen have no real plastic level but rise up in strength till about 10mm displacement and proceed to drop in strength slowly afterwards. Tests were halted at 15-20mm deformation and reached a maximum capacity of 51kN.

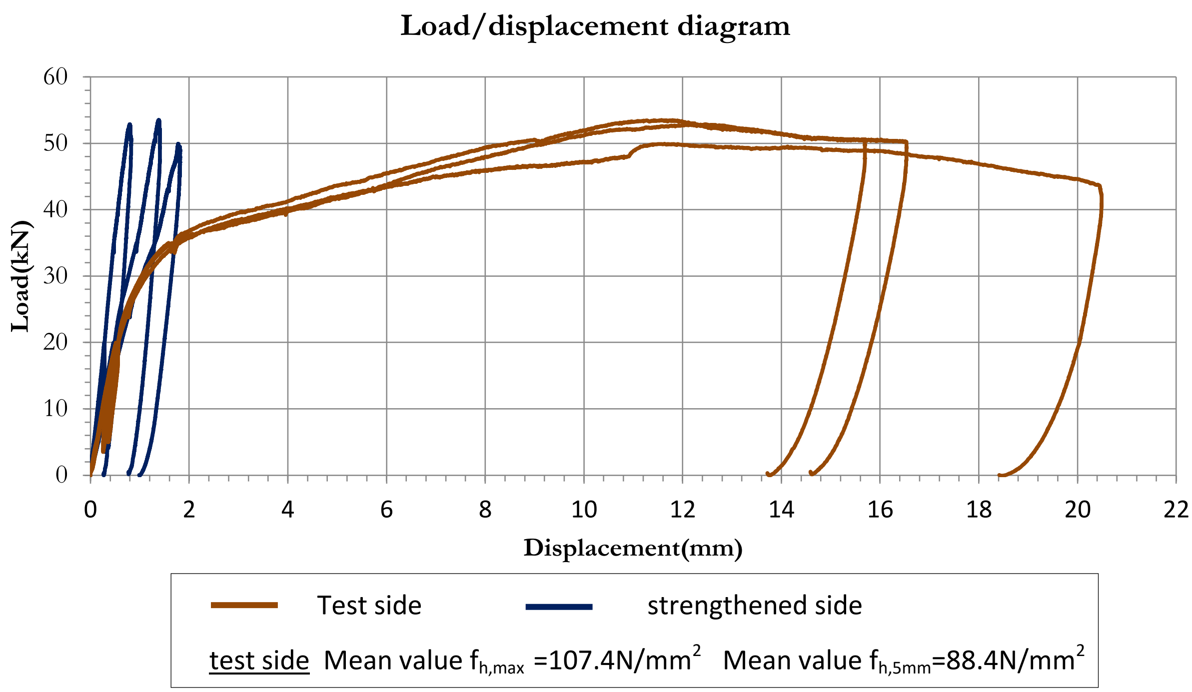


Figure 122 Load displacement diagram of T20_A45_N1

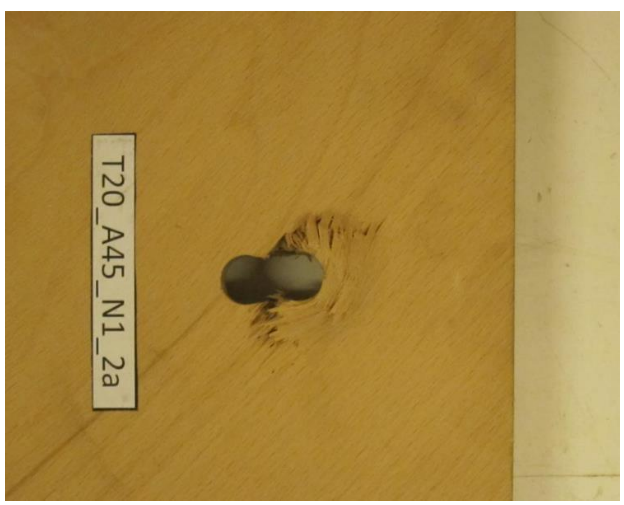


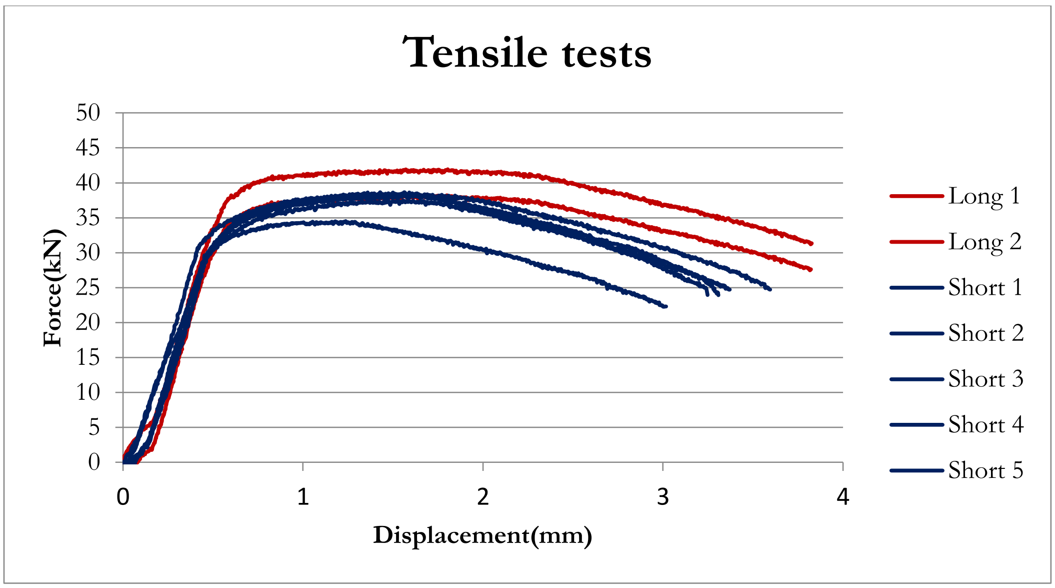
Figure 123 embedment failure in T20_A45_N1

8.5 Tensile tests on dowels

In the figure below the tensile tests on dowels used have been done. The ordered bolts were of strength 12.9.(f_y=1080 N/mm^2,f_u=1200N/mm^2). These values were met during experiments. The long bolts ordered reached slightly higher yield and ultimate strengths than the shorter bolts. Overall strength was higher than ordered but this was expected.

		Number of tests	Average (N/mm^2)	st.dev (N/mm^2)	cov (%)	5-percentile (N/mm^2)
Short	f_y	5	1247,71	62,95	5,05	1144,16
	f_u	5	1414,79	29,68	2,10	1365,97
Long	f_y	2	1355,94	17,22	1,27	1327,61
	f_u	2	1482,61	1,01	0,07	1480,94

table 24 Tensile tests dowels



9 Analysis

9.1 *Embedment behavior*

9.1.1 *Tests results*

In the table below relevant results of single dowelled tests are shown, this for analysis of the embedmentstrength. Dowels with more than 1 dowels could be influenced by the effects of ductility and spacing and are thus not picked at first for the comparison.

Test series	Number of tests	ρ_{mean}	$F_{\Delta 5mm}$	$\sigma_{st, \Delta 5mm}$	cov $F_{\Delta 5mm}$	Average force per dowel
T20_A0_N1	5	783	45,80	4,57	9,99	49,05
T20_A45_N1	3	793	42,43	1,07	2,51	51,57
T20_A90_N1	5	779	41,26	3,14	7,62	45,41
T20_A0_N1R	5	788	46,07	1,97	4,28	48,29

Table 25 Average force per dowel in single dowelled tests

Due to one experiment in the series of T20_A0_N1 with a low failure load the standard deviation is significantly larger than for other test series. Series T20_A0_N1R which is almost the same series, has twice less spread in results. Similar results are also found for experiments with 2 dowels which indicates that the values found in T20_A0_N1R should representative.

Test series	Number of tests (-)	mean density (kg/m^3)	$F_{\Delta 5mm}$ (kN)	$\sigma_{st, \Delta 5mm}$ (kN)	cov $F_{\Delta 5mm}$ (-)	Average force per dowel (kN)
T20_A0_N1R	5	788	46,07	1,97	4,28	48,29
T20_A0_N2R	5	790	92,49	4,63	5,00	48,37

table 26 Comparison tests with 1 and 2 dowels for reduced end distances

This comparison will be made with the embedment results found by Kobel[15] and by the design formula for plywood. In the literature study was found for Malaysian plywood(hardwood) that the embedment formula was slightly different but not unreliable. In this calculation is assumed that the plywood(below) meets the strength of design formula(8.36).

Embedment strength in solid timber:

$$f_{\mathrm{h},\alpha,\mathrm{k}} = \frac{f_{\mathrm{h,0,k}}}{k_{90}\sin^2\alpha + \cos^2\alpha} \qquad (8.31)$$

$$f_{\mathrm{h,0,k}} = 0{,}082(1 - 0{,}01d)\rho_{\mathrm{k}} \qquad (8.32)$$

For plywood:

$$f_{\mathrm{h,k}} = 0{,}11(1 - 0{,}01d)\rho_{\mathrm{k}} \qquad (8.36)$$

$$k_{90} = \begin{cases} 1{,}35 + 0{,}015d & \text{voor naaldhout} \\ 1{,}30 + 0{,}015d & \text{voor LVL} \\ 0{,}90 + 0{,}015d & \text{voor loofhout} \end{cases} \qquad (8.33)$$

Source formulas [13] EC5

LVL falls in neither category but is expected to be the middle ground of the two formulas.

9.1.2 Comparison with EC5

The density used for the comparison is based on the full sample size of the tests samples. These have been measured at the start of the experiments as seen below.

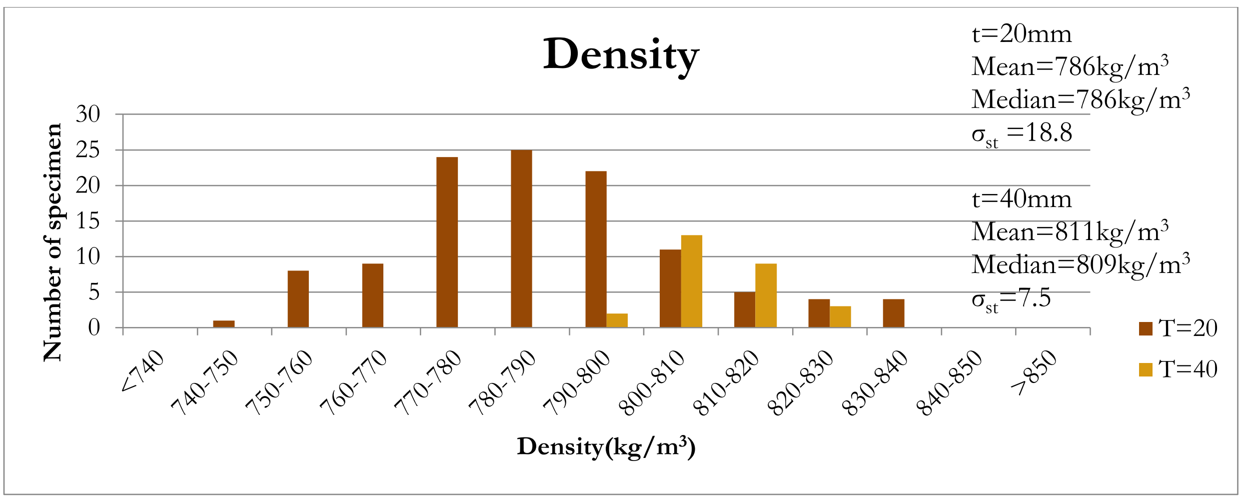


Figure 124 Density distribution in LVL-Q for T20(28% cross lamination) and T40(14% cross lamination)

$\rho_k = \rho_m - k*\sigma_{st}$ with k= 1.645 for calculating 5-percentile density

$\rho_k = 755 kg/m^3$

Because $f_{h,Fmax}$. is at an displacement that is too large comparisons are made with $f_{h,5mm}$.

In extreme cases namely with f_h at 45 degrees the embedmentstrength would be higher than when loaded parallel to the grain. This however requires deformations up to 15mm. That's why for this comparison embedment values at 5mm are used.

In Table 27 the embedment strength is calculated for the respective tests or design formulas.

$$F_{\Delta 5\text{mm},5\%} = F_{\Delta 5\text{mm}} - k * \sigma_{\text{st},\Delta 5\text{mm}}$$

$$f_h = \frac{F_{5mm}}{2*d*t}$$

Embedmentstrength for end distance 7d beech LVL-S source[15]
$f_{h,0,LVL}$ =72.0N/mm^2
$f_{h,0;k,LVL}$ =72.0N/mm^2-72N/mm^2*0.035*1.645=67.8 (COV=3.5%)

Embedmentstrength for end distance 5d beech LVL-S source[15]
$f_{h,0,LVL}$=49
$f_{h,0;k,LVL}$ =49.0N/mm^2-49N/mm^2*0.058*1.645=44.3 (COV=5.8%)

	$F_{\Delta 5mm}$ (kN)	$\sigma_{st,\Delta 5mm}$ (kN)	$F_{\Delta 5mm,5\%}$ (kN)	$f_{h,5\%}$ (N/mm^2)	notes
$f_{h,0,LVL}$ 7d				67.8	
$f_{h,0,LVL}$ 5d				44.3	*
$f_{h,45,LVL}$				65.2	*
$f_{h,90,LVL}$				62.8	
$f_{h,plywood}$				73,1	using (8.36) ρ_k =755kg/m^3
T20_A0_N1	45,80	4,57	38,3	79,8	
T20_A0_N1R	46,07	1,97	42,8	89,2	
T20_A45_N1	42,43	1,07	40,7	84,7	
T20_A90_N1	41,26	3,14	36,1	75,2	

Table 27 Results of tests and design formula used for comparison

*$f_{h;0}$=67.8N/mm^2 K_{90}=0.9+0.015*12=1.08 Determined using eq 8.31

Note: K_{90} is chosen at 0.9+0.015d because it was believe to be more accurate. The value 1.3+0.015d resembles very much the values found in that of softwood. This formulas are most likely derived from softwood LVL and give unrealistic values for hardwood LVL.

This leads to the following increase

	$f_{h,5\%}$ (N/mm^2)	$f_{h,5\%,LVL}$ (N/mm^2)	$f_{h,5\%,plywood}$ (N/mm^2)	Increase	notes
T20_A0_N1	79,75	67.8		18%	
T20_A0_N1R	89,22	44.3		101%	
T20_A45_N1	84,73	65.2		30%	
T20_A90_N1	75,18	62.8		20%	
T20_A0_N1	79,75		73,1	9%	
T20_A0_N1R	89,22		73,1	22%	
T20_A45_N1	84,73		73,1	16%	
T20_A90_N1	75,18		73,1	3%	

Table 28 Comparison of test formula vs solid timber and plywood

As seen in table Table 28, the perpendicular to the grain reinforcement of LVL-Q gives a significant improvement. Especially at lower end distances the improvement is very large. The reason for this is that splitting is not in LVL-Q. Table 28 is based on values at 5mm, noteworthy is that the values for LVL-Q are even larger at large displacement, but these are not taken into account in this comparison.

9.1.3 Design equation

Using the design formula(8.31 and 8.32) for solid timber, a fitting formula has been created using embedment values found at a displacement of 5mm:

Deriving the appropriate values for the equations for $f_{h;0;k;}$ and k_{90}:

Formula:8.32 EC5

$$f_{h,0,k} = 0{,}082(1-0{,}01d)\rho_k \tag{8.32}$$

For d=12mm; ρ_k=755kg/m^3; $f_{h,0,k}$=89.22N/mm^2
and
$f_{h,0,k}$=A*(1-0,01*d)* ρ_k
A=0.134

Formula:8.31 EC5

$$f_{h,\alpha,k} = \frac{f_{h,0,k}}{k_{90}\sin^2\alpha + \cos^2\alpha} \tag{8.31}$$

For $f_{h,0,k}$=89.22N/mm^2; $f_{h,90,k}$=75.18N/mm^2; d=12mm
and
k_{90}=B+0.015*d
B=1.0

This results into the following equations:

$f_{h,0,k}$=0.134*(1-0,01*d)* ρ_k

k_{90}=1.0+0.015*d

With the graph underneath comparing the design equation versus the test results:

$f_{h,0,k}$=0.134*(1-0,01*d)* ρ_k

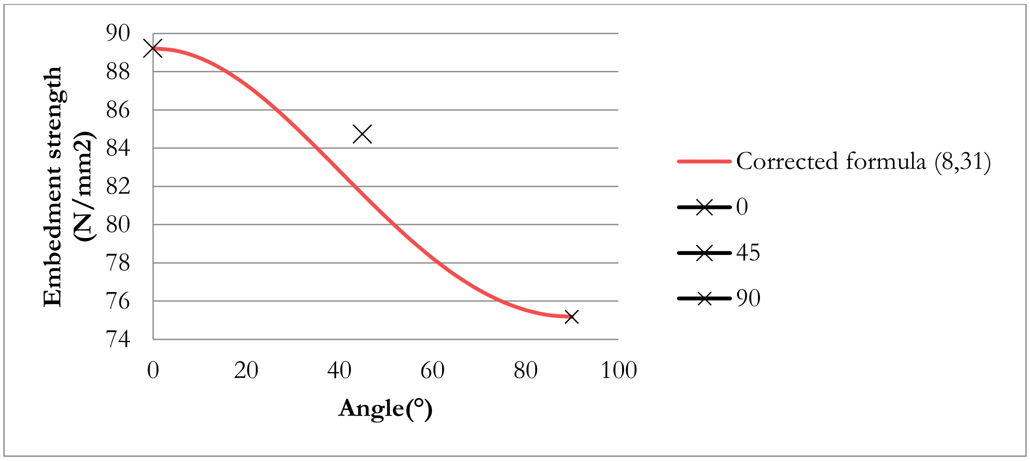


Figure 125 Corrected design equation 8,31 versus test results at 5mm

Because the specimen with FM-II can't be translated to a correct embedment strength which resembles the real embedment of LVL-Q with 14% cross lamination the results have been left out. Graph below is based on the following formula

- $f_{h,0,k}$=0.134*(1-0,01*d)*ρ_k for LVL-Q 28%
- k_{90}=1.0+0.015*d
- $f_{h,0,k}$=0.11*(1-0,01*d)*ρ_k for plywood
- k_{90}=1.0
- $f_{h,0,k}$=0.082*(1-0,01*d)*ρ_k for solid timber
- k_{90}=0.9+0.015*d
- $f_{h,0,k}$=72.0 for LVL-S(tests results Kobel[15])
- k_{90}=0.9+0.015*d

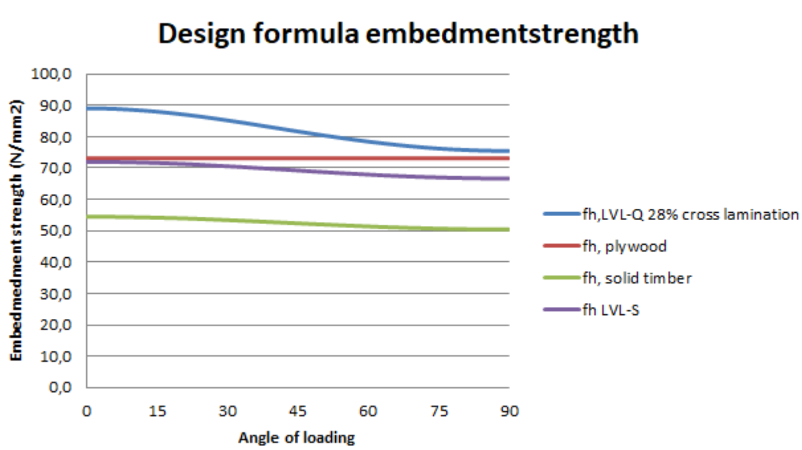


Figure 126 Comparison design equations(above) versus the corrected design equation for ρ_k=755kg/m^3,d=12mm

9.2 End distances and splitting

9.2.1 Splitting

Splitting occurred once during testing this occurred with specimen T20_A0_N2R_4(highlighted in graph below with red). The drop in strength should be mostly related to the block shear of a veneer at the steel plate, which led to a decrease in capacity. The final splitting actually occurred in the “undamaged” specimen. The exact reason why splitting occurred for this specimen is unknown as no other specimen shown any sign of splitting.

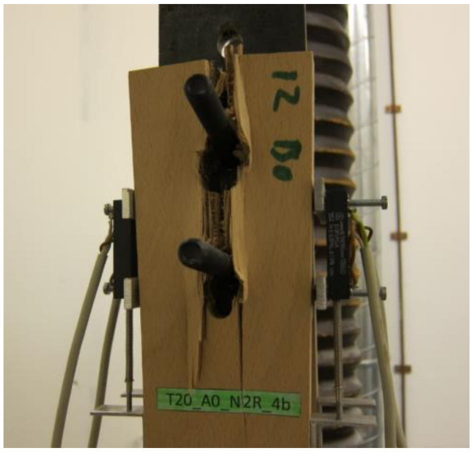


Figure 127 splitting failure in experiment T20_A0_N2R_4b

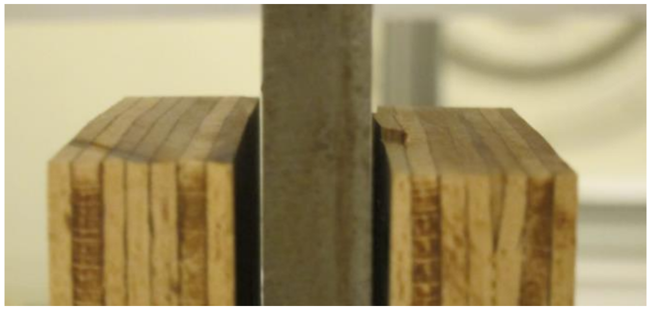


Figure 128 shearing of the veneer around 7-8mm

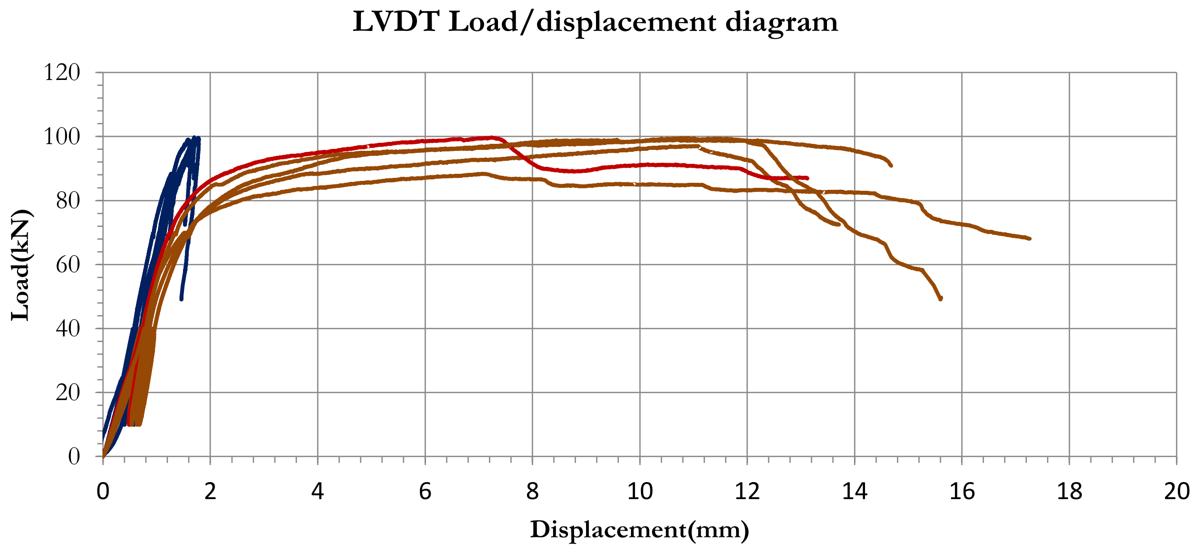
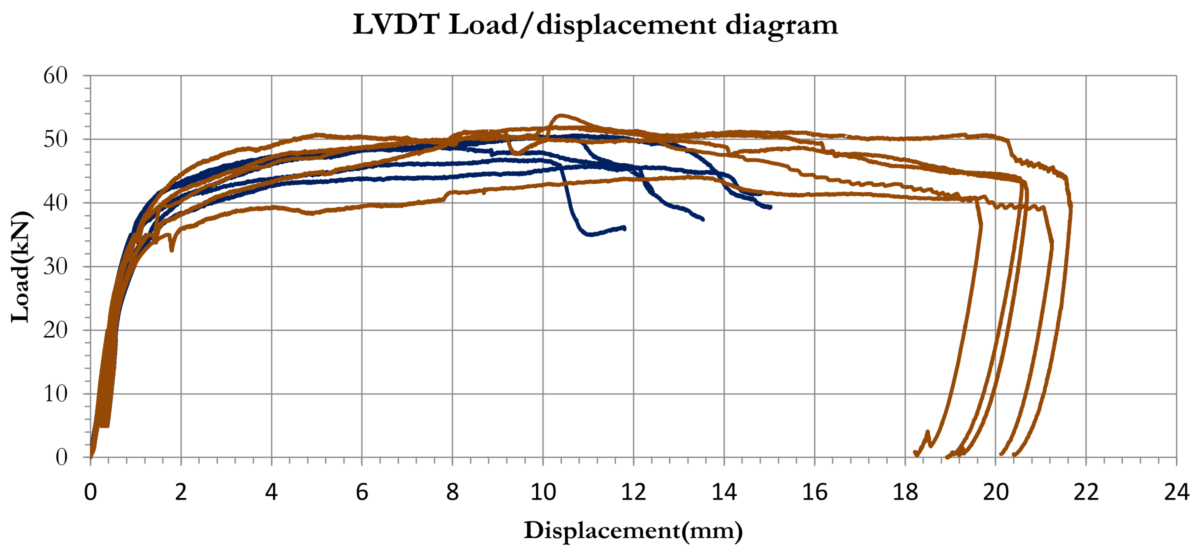


Figure 129 Load displacement curves of experiments T20_A0_N2(with red line showing experiment with splitting failure)

Splitting is most likely affected by the end distance, but for LVL-Q shear seems to be more governing. In addition to that the experiments set up suffered heavily from tensile failure which occurred earlier than predicted. The cause of this earlier tensile failure was likely due to damage around the veneers at larger deformations.

9.2.2 End distances and spacing

The end distances of specimen parallel to the grain were varied. The reduction of end distances from 7d from 5d did not affect the load carrying capacity, but did affect ductility. Experiments with an end distance of 5d where susceptible to shearing while those with and end distance tend to fail more ductile.



During testing it was observed that a lot of specimen experienced shear, not till failure but it did decrease the capacity. This resulted the locally shearing off some veneers. This is seen by small drops in the graph and are the result of shear failures in the connection.

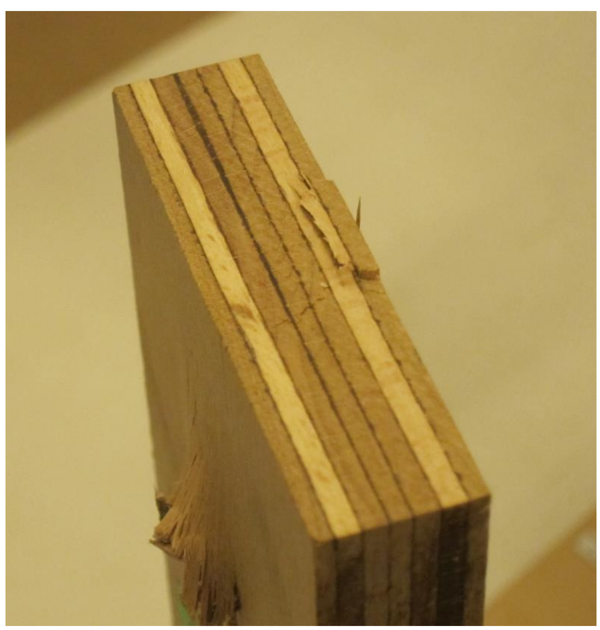


Figure 130 Local shear of veneers during loading

This happened regularly in between the dowels for specimen. For specimen with a thickness of 20mm and thus a higher cross layer percentage the shear resulted mostly in a plug shear failure. While for timber with a thickness of 40mm mostly shear between the transition from parallel layer to cross layer at the surface against the steel plate. The cause for this is either that failure mode II resulted in a more unequal stress distribution or due to the lower level of cross layers in a thickness of 40mm.

Nominal component thickness in mm	Number of veneer layers longl	crossw.	total	Composition
20	5	2	7	I-III-I
30	9	2	11	II-IIIII-II
40	12	2	14	III-IIIIII-III
50	16	2	18	III-IIIIIIIIII-III
60	17	4	21	III-II-IIIIIII-II-III
70	20	4	24	III-II-IIIIIIIIII-II-III
80	23	4	27	III-II-IIIIIIIIIIIII-II-III
I	longitudinal veneer layer			
-	crosswise veneer layer			

Figure 131 Cross layer composition LVL-Q

This unequal stress distribution is explained below

There will always be some internal stresses due to stiffness differences in the cross section.
However in FM-II the real embedment distribution adds additional stresses due to a non-linear embedment stress

When this internal differences has to be transfered from 1 layer to the other failure occurs at the layers adjacent to cross veneers
As in this case the force is transfered through rolling shear instead of regular shear

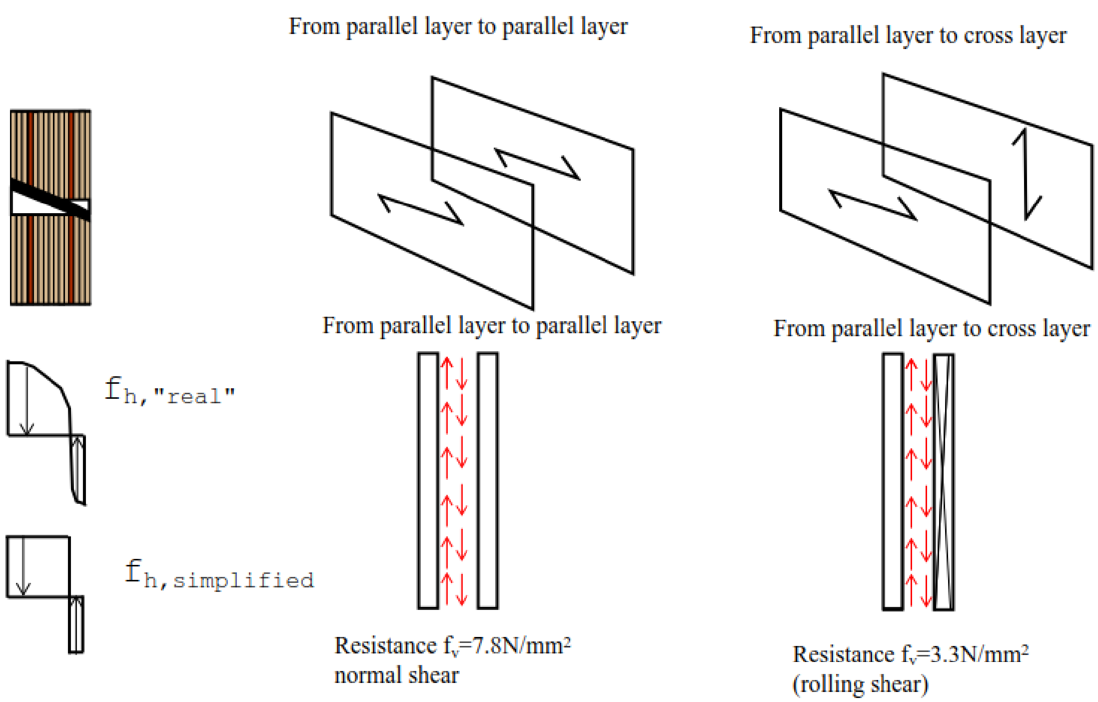


Figure 132 Full shearing betweens dowels

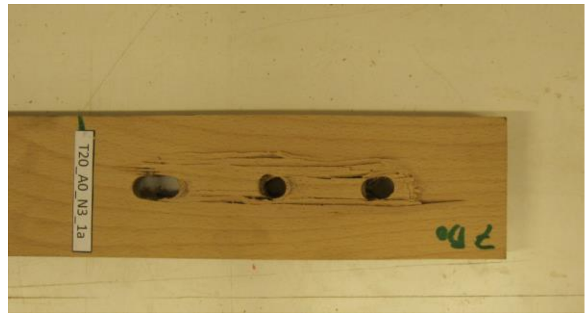


Figure 133 partial shearing between dowels

Figure 134 top veneers shearing betweens dowels

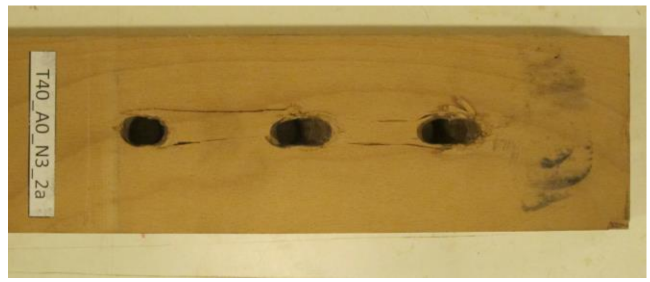


Figure 135 top veneers shearing between dowels

The unequal stress distribution results in shear stresses in the cross section. In this case the veneers connection to cross layers are the weakest link in the cross section which tend to fail first. This is even more present in FM-II which leads to an uneven strain distribution from left to right due to the dowel bending.

The shearing of the veneers didn't always occur, the specimen with an 7d end distance didn't shear off at the veneers, while those with an 5d end distance did. See the pictures below.

Figure 136 Test specimen T20_A0_N1_1a showing no shear failure

Figure 137 Test specimen T20_A0_N1R_3b showing shear failure

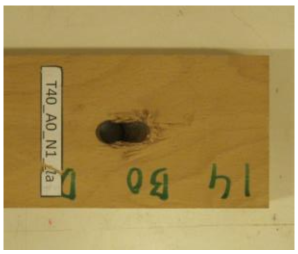


Figure 138 Test specimen T40_A0_N1_1a showing no shear failure

Figure 139 Test specimen T20_A0_N2_3b showing shear failure between the dowels

Figure 140 Test Specimen T40_A0_N2_2b showing shear failure between the dowels

What was notable that the veneer distribution is different for t=20mm and t=40mm. Leading to specimen t=40mm almost always shearing at surface against the steel plate, while those with a thickness of t=20mm could shear at the surface, locally as block shear or a full plug shear failure.

The choice of spacing between the dowels with LVL-Q is likely best at 7d to prevent any brittle failures such as shear.

9.3 Effective number of dowels

Due to experiments failing to tensile it was more difficult/impossible to give a singular analysis of the effect of multiple dowels in connections. However due to the tensile failure occurring at a high load an lower boundary can be made.

$$n_{ef} = \min\begin{cases} n \\ n^{0,9}\sqrt[4]{\dfrac{a_1}{13d}} \end{cases}$$

n_{ef}=1.46 for 2 dowels at 5d spacing
n_{ef}=2.11 for 3 dowels at 5d spacing

Using the data from the experiments the values below are presented. A difference is made again between F_{max} the maximum failure load at any distance or F_{5mm} which is the failure load at 5mm displacement.

	$F_{max,mean}$ (kN)	$F_{5mm,mean}$ (kN)	$F_{max,n1}/F_{max,n}$ (-)	$F_{5mm,n1}/F_{5mm,n}$ (-)	n_{ef} F_{max} (-)	$n_{ef,}$ F_{5mm} (-)	$n_{ef}, F_{max}/n$ (-)	$n_{ef}, F_{5mm}/n$ (-)
T20_A0_N1	49,1	45,8	1	1	1	1	1,00	1,00
T20_A0_N2	48,7	46,2	0,99	1,01	1,98	2,02	0,99	1,01
T20_A0_N3	45,9	44,7	0,94	0,98	2,81	2,93	0,94	0,98
T20_A0_N1R	48,3	46,1	1,00	1,00	1	1	1,00	1,00
T20_A0_N2R	48,4	46,2	1,00	1,00	2,00	2,01	1,00	1,00
T20_A0_N3R_S	46,3	47,2	0,96	1,02	2,88	3,07	0,96	1,02
T20_A90_N1	45,4	41,3	1,00	1,00	1	1	1,00	1,00
T20_A90_N2	41,5	38,3	0,91	0,93	1,83	1,85	0,91	0,93
T20_A90_N3	39,3	0,0	0,87	0,00	2,60	0,00	0,87	0,00
T40_A0_N1	65,7	54,3	1,00	1,00	1	1	1,00	1,00
T40_A0_N2	56,6	52,1	0,86	0,96	1,72	1,92	0,86	0,96
T40_A0_N3	54,9	53,4	0,83	0,98	2,50	2,95	0,83	0,98
T40_A90_N1	53,6	49,0	1,00	1,00	1	1	1,00	1,00
T40_A90_N2	53,8	48,2	1,00	0,98	2,01	1,97	1,00	0,98
T40_A90_N3	47,6	49,1	0,89	1,00	2,67	3,00	0,89	1,00

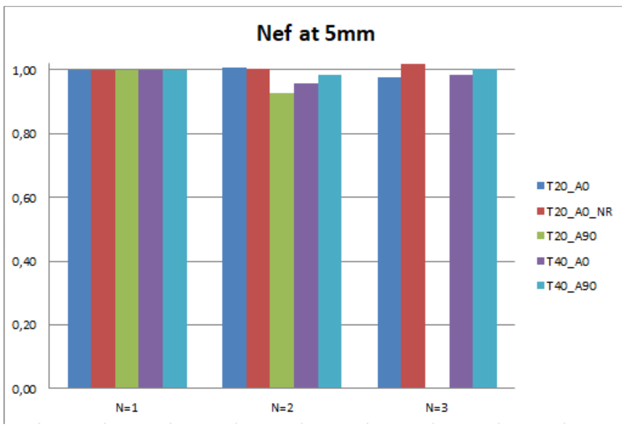
Table 29 Average values of Fmax and n_{ef}

When looking at the graphs the drops in n_{ef} at F_{max} can be explained by the following reasons.

- Drop in n_{ef} for T20_A90 and for T40_A90 are caused by tensile failure of the net cross section resulting in a lower strength
- Drop in n_{ef} for T40_A0 are caused by the opening of the gap between steel and timber and the shearing of the top veneers at a spacing of 5d. When taken as 7d this is likely to be prevented.

n_{ef} is very close to 1 when loaded parallel to the grain. The result when loaded perpendicular to the grain is slightly shifted because of the tensile failures that occurred. A higher value could be acquired when tensile failure at the net-cross section is prevented. This would make a better comparison.

But overall the results are positive a lot of deformation capacity was achieved by the ductility of the LVL resulting in much higher values than were found by [16] which only had a n_{ef} of about 2.



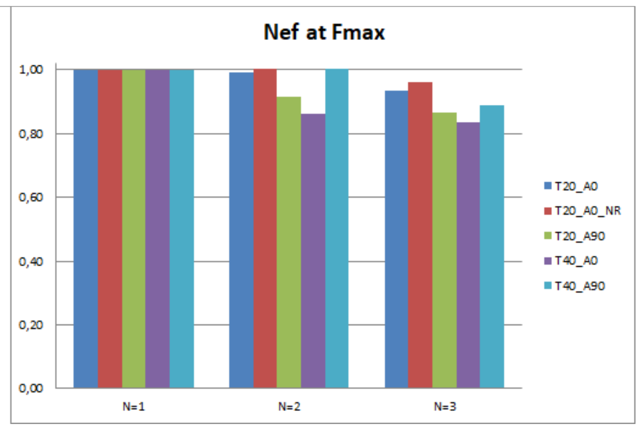


Figure 141 Comparison n_{ef} for test specimen T20 and T40

9.4 *Tensile failure net cross section*

Because in an earlier stage preparation a mistake was made tensile failure in the net cross section was expected. However this was expected for 3 dowels instead of 2 dowels.

$$F_{R,t} = (w - d) \cdot t \cdot f_t$$

Load direction (°)	Dowel diameter d (mm)	Thickness t (mm)	Width W (mm)	Characteristic tensile strength f_t (N/mm^2)	Tensile capacity per element $F_{R,t}$ (kN)	Tensile capacity *2 $F_{R,t}$ (kN)
0	12	20	80	45	61,2	122.4
90	12	20	240	16	72,96	145.92
0	12	40	80	51	138,72	277.44
90	12	40	240	8	72,96	145.92

table 30 Tensile capacity timber

	Tensile capacity (x2) $F_{R,t}$(kN)	Failure load F_{max} (kN)
T20_A0_N2	122.4	97.33
T20_A0_N2R	122.4	96.74
T20_A0_N3	122.4	137.76
T20_A0_N3R_S	122.4	139.04
T20_A90_N2	145.92	83.08
T20_A90_N3	145.92	117.95
T20_A90_N3_S	145.92	119.76
T40_A90_N2	145.92	107.61
T40_A90_N3	145.92	142.91

table 31 Comparison tensile capacity vs failure load

The failure before reaching the tensile capacity is likely caused due by the high stresses near the dowel inducing tensile failure at the net cross section. These tensile failure occurred below the characteristic strength of the timber.

When this failure occurred significantly beneath the tensile capacity it was mainly occurred at a larger displacement than 5mm. For two dowels at a displacement of approximately 7-12mm which was the zone at which visible damage around the dowel holes was seen.

For 3 dowels this tensile failure occurred at an earlier displacement but at a higher load, which was above the tensile capacity. It was noteworthy that some of the test with T20_A0_N3 were strengthened by clamping them together. This resulted in reaching slightly higher strength than usual but this could be coincidence. I expect that the deformation is likely to be a bit better spread across the cross section leading to less vulnerability to these peak stresses.

Specimen in T20_A90_N2,3 also most likely failed earlier to the tensile failure at the net cross section due t that it was unable to spread the tensile stresses evenly over the full cross section.

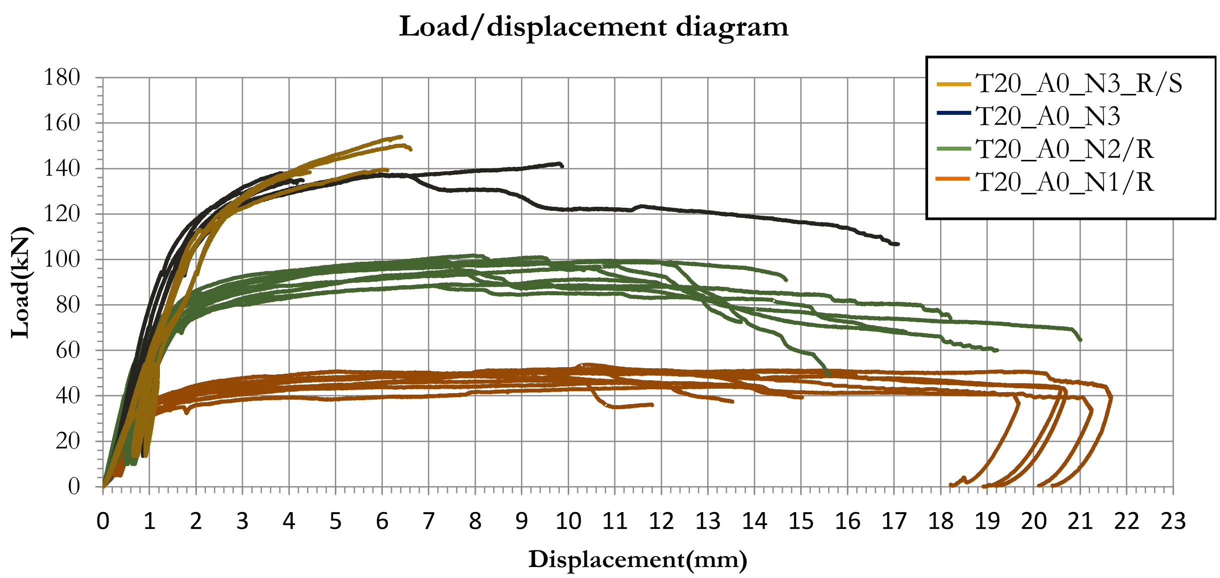


Figure 142 Load displacement diagram of test specimen

9.5 *Densification and cord effect*

During the experiments was found that clamping the specimen together had a positive effect on the embedment strength. Normally the cord effect is not used for failure in mode I, however the specimen T20_A0_N1_S and T20_A0_N1_S started to show slight dowel deformations. This deformation is difficult to capture, but when holding the dowel in hand you can see some deformation.

When the bolts were applied hand tight(no wrench), it was impossible to remove the bolts without a wrench after unloading. There was a significant tension present in the bolt which indicates that the extra strength observed was due to the rope effect.

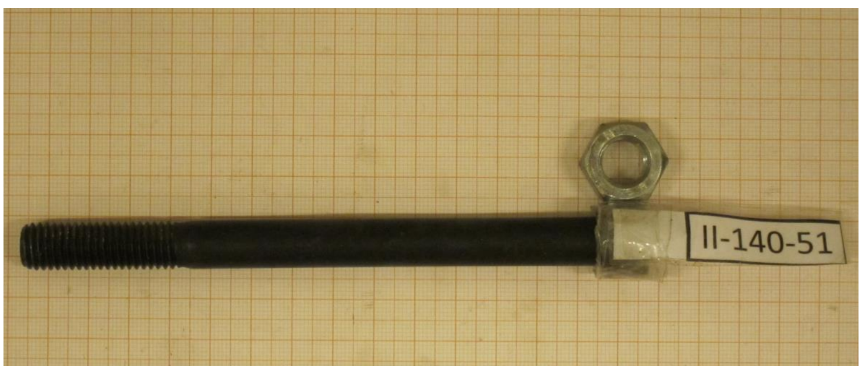


Figure 143 Very slight dowel deformation at test side in specimen T20_A0_N3_S

Figure 144 setup specimen T20_A0_N3_S

In this case the rope effects causes two different effects.(see Figure 145)

- The axial force $F_{ax,h}$ gives an compression force that prevents the wood from pushing outward and allows the wood to be densified behind the dowel. This results into an increased embedment strength
- The axial force $F_{ax,v}$ which is normally added to the resistance in FM-II and FM-III. In these experiments the specimen were close to the boundary between FM-I and FM-II this can also be confirmed by the permanent deformation in the dowel. Hence it quite likely that the rope effect was present.

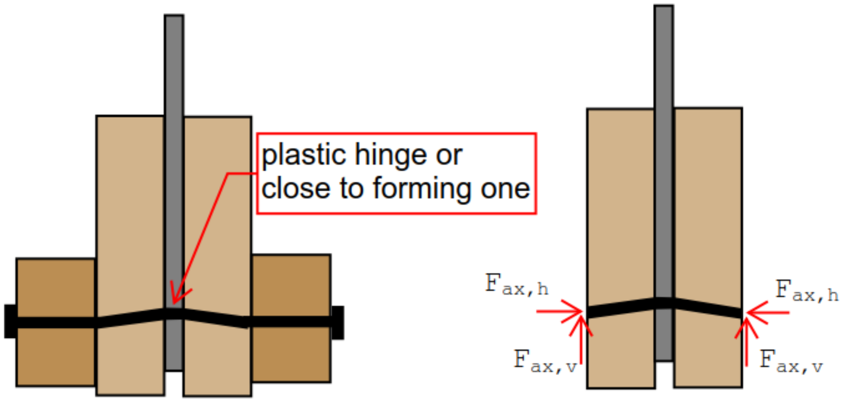


Figure 145 Principle rope effect in FM-II

Figure 146 densification behind dowel with a specimen clamped together

Figure 147 Timber deformation pushing outwards

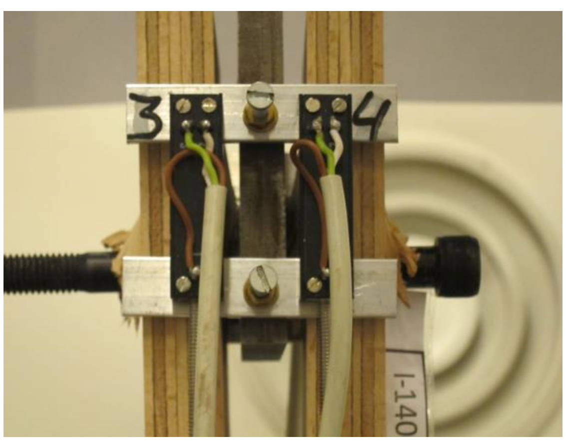


Figure 148 Timber pushing itself away from steel plate due to deformation when not clamped together

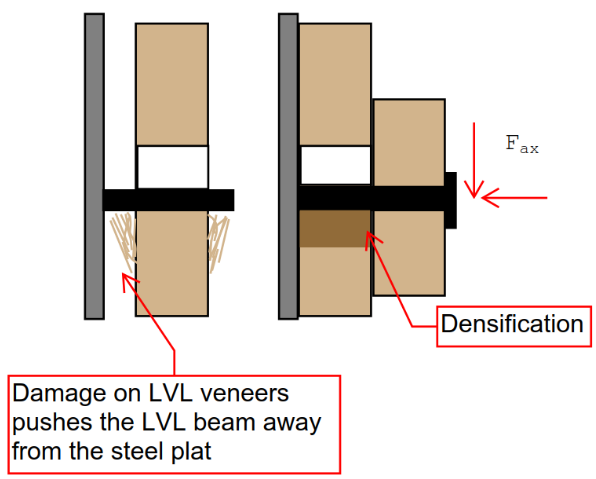


Figure 149 Principle of densification behind the dowel

10 Design moment resisting connection

For comparison a few timber connection are calculated according to the corrected formulas from the analysis. For a moment resisting connection is calculated using the a simplified formula of the embedment and stiffness found during the experiments.

The moment capacity has been determined on the beams below. This beams have ideal dimension for the given connection leading to the best ratio in moment capacity connection vs moment capacity beam.

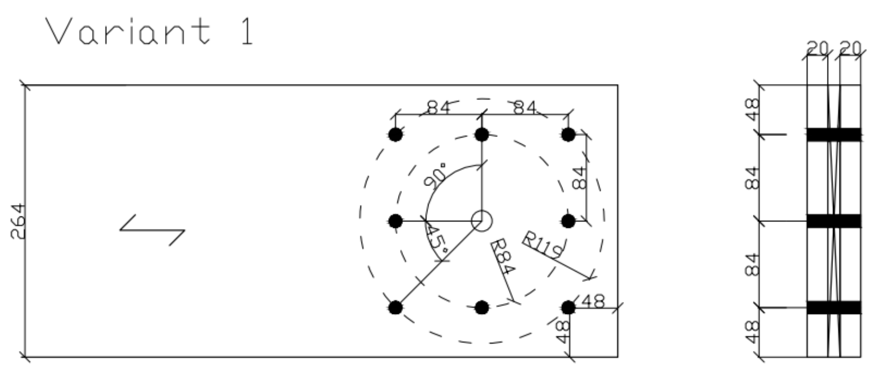


Figure 150 Variant 1 designed to fail in failure mode I

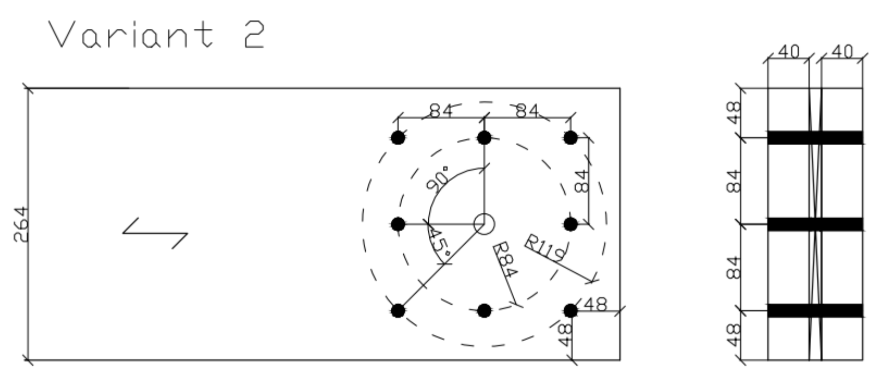


Figure 151 Variant 2 designed to fail in failure mode II

Embedmentstrength is given by:

$f_{h;\alpha} = -\frac{f_{h;\alpha;5mm}}{9} * u^2 + \frac{f_{h;\alpha;5mm}}{1.5} * u$ for $0 \leq u < 3$

$f_{h;\alpha} = f_{h;\alpha;5mm}$ for $u > 3$

u=displacement of respective dowel

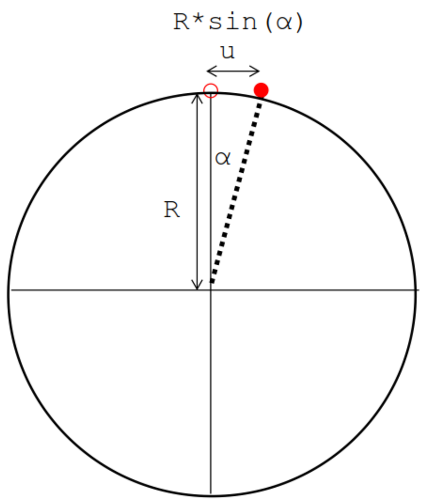


Figure 152 Calculation displacement u for rotation α

The curve has been slightly move forward to 3mm(instead of 5) to fit the curves better found in the experiments.

With

$k_{90} = 1.0 + 0.015 * d \; for \; LVL - Q$

$k_{90} = 0.9 + 0.015 * d \; for \; LVL - S$

Note that the K_{90} value is chosen at the value of solid beech instead of LVL. (this because LVL design formula is likely derived from spruce LVL instead of hardwood LVL).

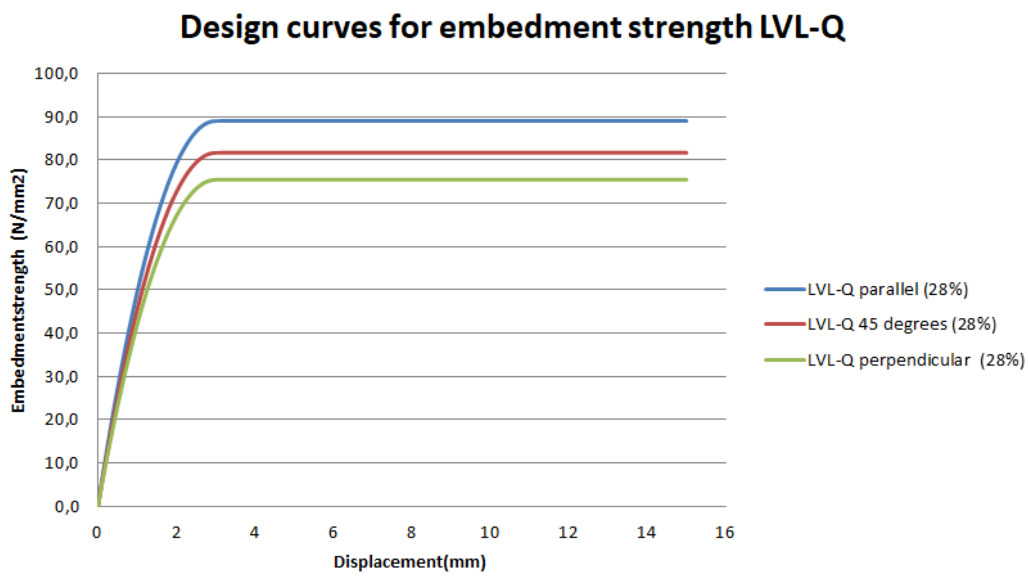


Figure 153 Design curves according to formulas below for LVL-Q

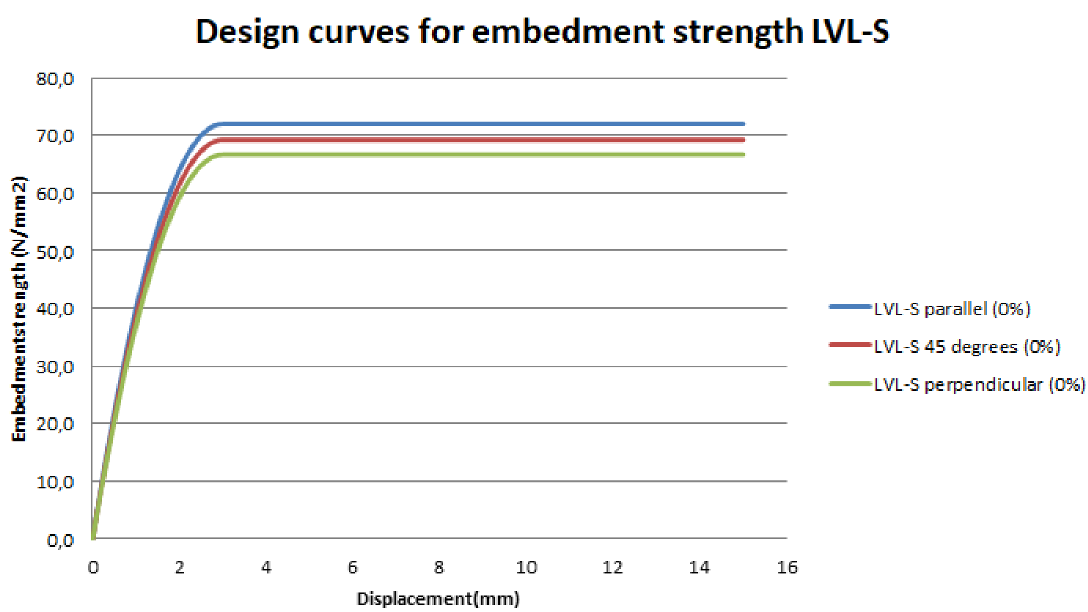


Figure 154 Design curves according to formulas below for LVL-S

On the next page the design curves are compared with the appropriate experiments to show that they fit(For LVL-Q). No comparison is made with LVL-S as there is not full set of data. The shape has been compared which you can see in the figure below.

The shape for FM-II/FM-III can be found in Misconel et al[16] while the embedment strength used comes from Kobel et al[15]. And leads to the graphs as shown above for LVL-S.

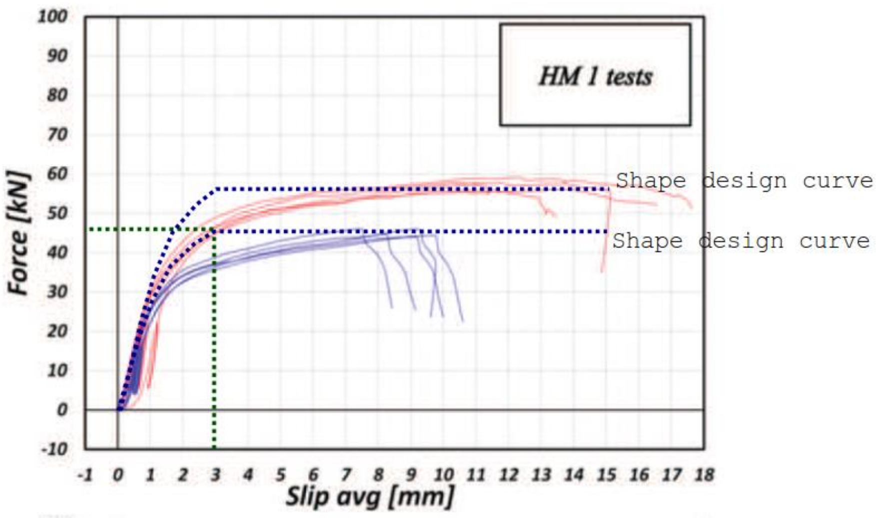


Figure 155 fitting shape design curve into connections test in FM-II[test results [16]) ($f_{h,max}$=72N/mm^2 for LVL-S found in [15])

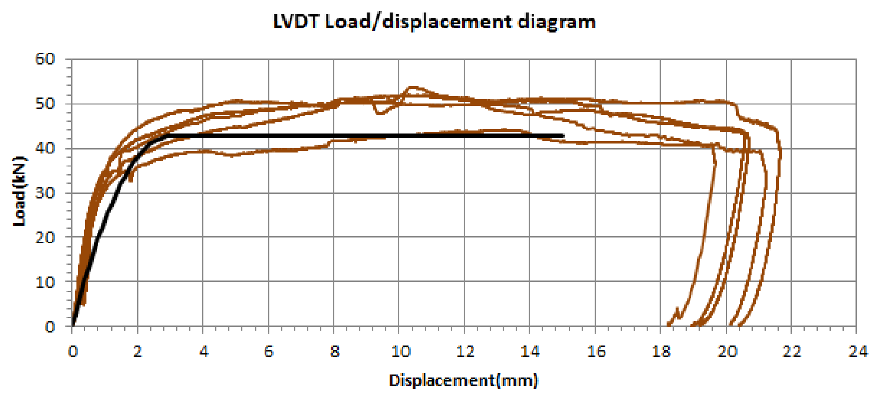


Figure 156 Comparison fitting curve with T20_A0_N1(black=design curve, brown=tests)

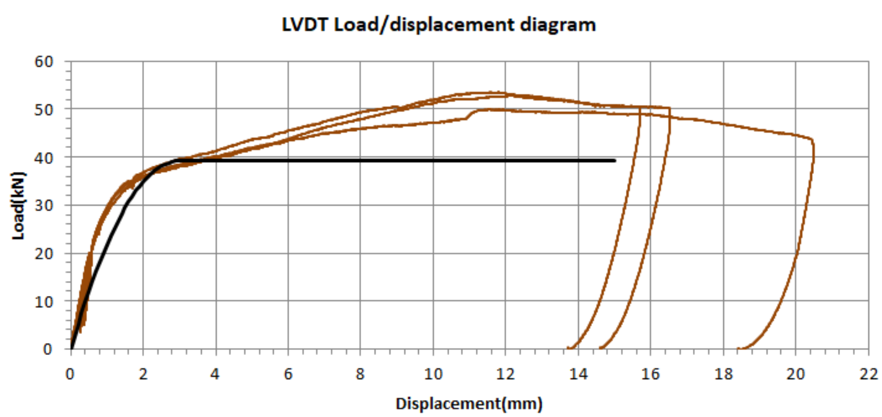


Figure 157 Comparison fitting curve with T20_A45_N1(black=design curve, brown=tests)

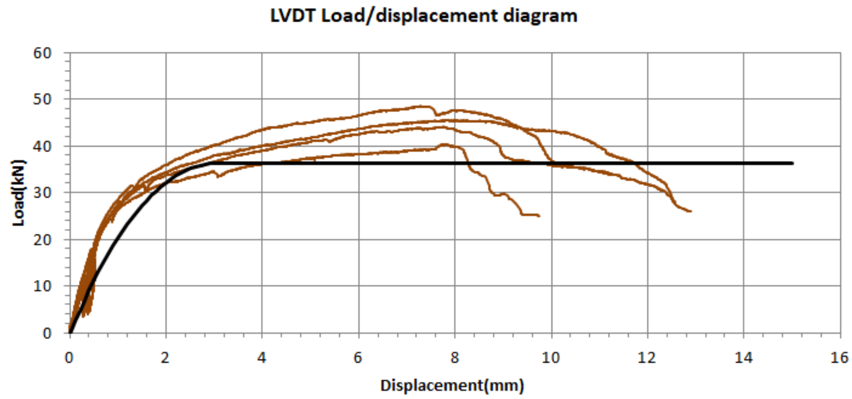


Figure 158 Comparison fitting curve with T20_A45_N1(black=design curve, brown=tests)

Both test are compared for VHSS

- M_y=1/6*fy*d^3
- And steel quality 12.9

Based on the failure mechanisms(f,g,h) the strength was determined. These are the design formulas as used in the EC5.

$$F_{v,Rk} = \min \begin{cases} f_{h,1,k} t_1 d & \text{(f)} \\ f_{h1,k} t_1 d \left[\sqrt{2 + \dfrac{4 M_{y,Rk}}{f_{h,1,k} d t_1^2}} - 1 \right] + \dfrac{F_{ax,Rk}}{4} & \text{(g)} \\ 2{,}3 \sqrt{M_{y,Rk} f_{h,1,k} d} + \dfrac{F_{ax,Rk}}{4} & \text{(h)} \end{cases} \quad (8.11)$$

Design variant 2: $F_{vk;FM2} < F_{vk;FM3} < F_{vk;FM1}$

This way enough ductility is ensured in the connection. For variant 1 this is not necessary as the ductility is gained from the embedment deformation itself.

$M_{rd} = \frac{1}{6} b * h^2 * f_m \; with \; b = 2 * t \;, h = 264 \; f_m = 54N/mm^2$ for LVL-Q

$M_{rd} = \frac{1}{6} b * h^2 * f_m \; with \; b = 2 * t \;, h = 264 \; f_m = 75N/mm^2$ for LVL-S

Moment resisting capacity of the connection is calculated through the following formula.

$$M_{rd;connection} = \sum_{i=1}^{3} R_i * F_{vk;i}(u) n_{;i}$$

	Angle (°)	Ri (mm)	ni (-)	$F_{vk;i(max)}$ (kN)
LVL-Q(28%)	0	84	2	42,7
	45	119	4	39,2
	90	84	2	36,2
LVL-S(0%)	0	84	2	48,6
	45	119	4	47,4
	90	84	2	46,3

table 32 Data used for determination of moment capacity

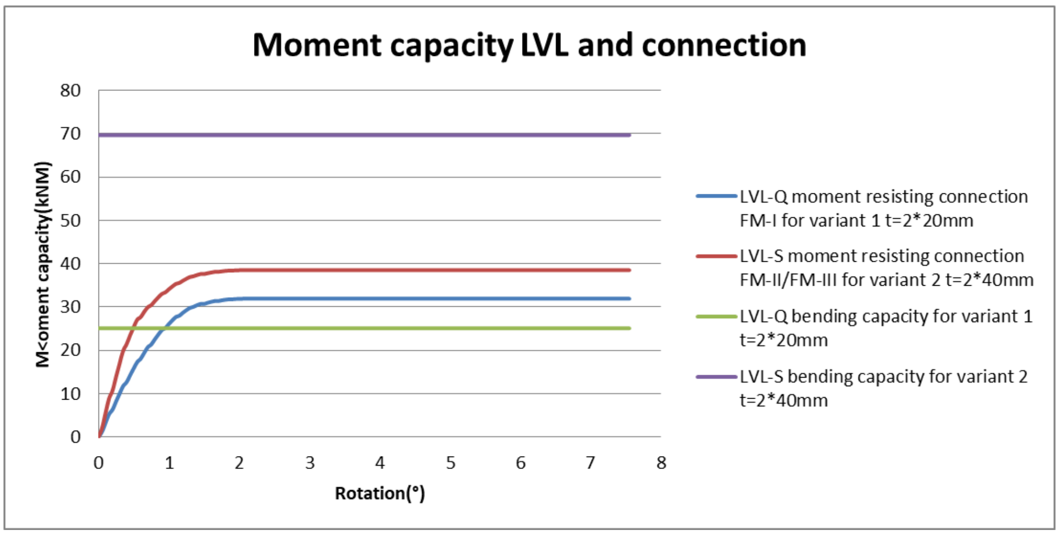


Figure 159 Moment rotation diagram bending capacity timber vs connection

	$M_{connection}$ (kNm)	M_{timber} (kNm)	$M_{connection}/M_{timber}$ (-)
LVL-S	31,9	25,1	1,27
LVL-Q	38,5	69,7	0,55

table 33 results capacity timber and connection(T-S-T)

Checking shear force stresses in connection

$$F_v = 2 * \frac{1}{2}\sqrt{2} * F_{45} + F_{90}$$

$$\tau_v = \frac{3 * F_v}{2 * t * h}$$

$$\tau_v = \frac{3 * (\sqrt{2} * 39.2 + 36.2)}{2 * 40 * 264} = 13.01 N/mm^2$$

$$13.01 N/mm^2 < 7.8 N/mm^2$$

$$\frac{13.01}{7.8} = 1.67$$

A unity check of 1,67 is present. This means there is not enough shear capacity in the connection for FM-I. Additional research is required to see if this is truly present as for the dowel shear force also at significantly higher strengths than was mentioned in the product specifications.

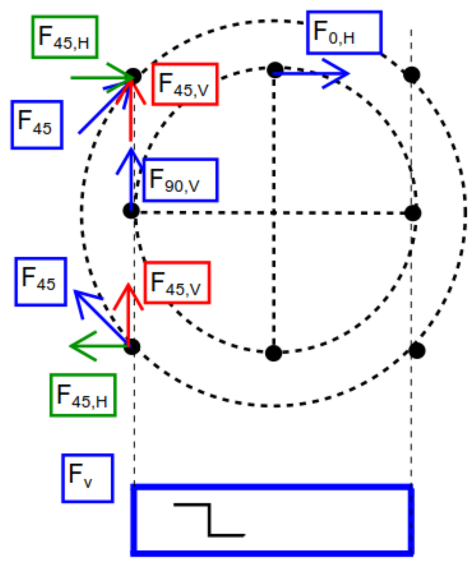


Figure 160 Shear force in joint due to dowel loads

In the comparison between variant 1 and variant 2 we can see that the connection in LVL-Q is stronger than the timber. This is not the case for LVL-S. The reason for this is quite simple:

- To acquire FM-II/FM-III timber has to be thick enough. Increasing the thickness also increasing the bending strength(in general) and thus the strength of LVL-S is lower relative to the timber.
- Also the bending strength of LVL-S is higher which also contributes to a more negative ratio of $M_{connection}/M_{timber}$

With LVL-Q showing almost the same ductility in FM-I as LVL-S does in FM-II.

The ratio of 1,27 shown in the table will be the same for every type of T-S-T or T-T-T, as long as the above dimensions are used and FM-I is governing. The design formula for FM-I are practically the same for all type of T-T-T(timber to timber double shear), T-T(timber to timber single shear), S-T(steel to timber single shear) connection. And thus only 1 calculation will be made.

Shear stresses however become too high in the connections additional research is needed for this to check at what moment this occurs.

11 Conclusion

The idea of using FM-I in combination with LVL-Q looks to be a promising idea. As long as enough shear planes are creating to stay in FM-I the efficiency of the connection is significantly larger. This allows for the creation of a moment resisting connection in LVL-Q timber which is stronger than the beams its connected to(given de dimensions as in paragraph 9). While the ductility is excellent in regards to FM-I, the timber is also very much improved for other failure modes. However the increased strength causes a different problem, In current design the connection will fail due to shear stresses in middle plane of the joint. Additional research is needed for this since the shear strength turned out to be higher for the dowels as well. Thus it needs to be verified that the shear stresses cause failure in the joint for moment resisting connections.

The observed embedment strength is significantly higher than for other wood products. Due to embedment strength and better splitting resistance other failures start to develop. Which is with the experiments primarily the shearing of veneers. This occurs mostly at a deformation at more than 5mm. An end distance and spacing of 7d seems to solve this issue. Summarizing the benefits of LVL-Q compared to the use of standard timber are:

- Embedmentstrength increase of 18-30% compared to LVL-S
- Embedmentstrength increase of 3-22% compared to plywood of equal density
- High ductility, deformations of up to 15mm(probably even higher)
- n_{ef} almost equal to the amount of dowels
- Higher splitting resistance

Whether timber doesn’t split in moment resisting connection is still uncertain, the resistance is certainly expected to be improved. Single doweled specimen loaded perpendicular to the grain showed no sign of splitting thus it is likely that the splitting resistance has been significantly improved. This however still requires experimental testing in a moment resisting connection setup.

The end distance as given by the Eurocode 5 is suitable for LVL-Q, the spacing of 5d between dowels is questionable however. To use the full strength of a single dowel in LVL-Q I believe the minimum end distance and spacing should be equal to each other thus 7d spacing.

Overall LVL-Q seems to be a promising material, the strength is much higher than expected. The moment capacity of the connection exceeded that of the structural element it was connected to. The current width over height ratio is a bit impractical in the example, but this can be further improve by a connection with multiple steel plates/shears planes to improve the dimensions.

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[7] https://www.youtube.com/watch?v=kYYFDC3kFJM BauBuche Product information (*This is an video on the production process of BauBuche and screenshots have been taken to show the product process in this report)*

[8] https://www.pollmeier.com/

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13 Appendix

13.1 *Data experiments*

13.1.1 *Dimensions, weight and dynamic frequency*

Specimen	Ttop (mm)	Tbot (mm)	Wtop (mm)	Wbot (mm)	Length (mm)	Weight (g)	Frequency (hZ)	Density (kg/m3)
1	20,08	20,15	80,09	79,79	652	830,2	3211	791,9
2	20,21	20,21	79,46	80,2	652	834,1	3221	792,9
3	20,19	20,25	80,18	79,88	652	834,3	3089	790,8
4	20,21	20,32	79,89	79,85	652	831	3128	787,5
5	20,22	20,2	79,8	79,85	652	836	3231	794,8
6	20,23	20,25	80	79,94	652	858,3	3250	813,3
7	20,11	20,14	79,96	80,06	652	804,9	3162	766,7
8	20,17	20,17	79,89	79,95	652	812,5	3201	773,1
9	20,3	20,3	79,83	79,96	651	807,7	3157	765,0
10	20,22	20,23	80,04	79,9	651	816	3221	775,0
11	20,23	20,23	79,92	79,79	651	827,1	3250	786,5
12	20,25	20,22	79,95	79,33	651	834,3	3231	795,3
13	20,08	20,13	80,08	80,15	652	820,1	3270	780,9
14	20,2	20,18	79,84	79,91	652	825,5	3226	785,1
15	20,2	20,19	79,91	79,92	652	821,6	3304	780,8
16	20,21	20,2	79,89	79,83	652	785,4	3177	746,5
17	20,3	20,21	79,92	79,71	651	824,6	3240	783,5
18	20,32	20,2	80,13	79,62	652	846,6	3353	802,4
19	20,3	20,1	80,12	80,1	653	801,6	3265	758,6
20	20,27	20,15	79,85	79,9	652	802,5	3279	762,5
21	20,23	20,21	79,88	80,05	653	810,6	3284	767,7
22	20,26	20,23	79,86	79,79	651	794,5	3206	755,2
23	20,21	20,21	79,98	79,35	652	810,5	3231	772,1
24	20,25	20,22	80,1	79,12	652	822,3	3299	782,9
25	20,14	20,1	80,08	80,02	653	802,2	3162	762,7
26	20,37	20,15	80,06	79,92	652	796,9	3157	754,2
27	20,2	20,19	79,93	79,88	651	815,3	3192	776,1
28	20,25	20,21	80,06	79,97	651	810,3	3148	768,9
29	20,23	20,22	80,07	79,73	651	803,5	3157	763,8
30	20,29	20,3	79,96	79,43	651	815,8	3172	774,8
31	20,21	20,11	80,01	80,11	651	796,7	3040	758,2

32	20,18	20,15	79,97	80,01	652	813,2	3113	773,2
33	20,33	20,2	79,9	79,98	651	828,1	3206	785,2
34	20,42	20,23	80	79,93	651	826,7	3182	781,3
35	20,21	20,21	79,89	79,77	651	828	3094	788,3
36	20,24	20,25	80,08	79,51	651	819,1	3089	778,9
37	20,02	20,03	80,09	80,44	650	808,7	3143	774,1
38	20,12	20,11	80,46	80,33	650	820,2	3113	780,3
39	20,13	19,99	80,5	80,52	650	829	3070	789,7
40	20,17	20,01	80,39	80,35	650	830,4	3162	791,2
41	20,2	20,01	80,34	80,39	650	832	3123	792,2
42	20,15	20,01	80,53	80,21	650	830,8	3177	792,0
43	20,17	20,02	80,41	80,42	650	823	3065	783,5
44	20,21	20	80,42	80,38	650	833,3	3118	793,1
45	20,19	20,04	80,37	80,34	650	833,2	3089	793,1
46	20,2	20,04	80,39	80,49	650	846,7	3177	804,9
47	20,19	20,01	80,41	80,38	650	853	3143	812,1
48	20,23	20,02	80,46	80,39	650	844,7	3094	802,9
49	20,21	20,05	80,46	80,16	650	843,1	3148	802,3
50	20,04	20,11	80,15	80,44	650	806,2	3001	769,5
51	20,13	20,14	80,44	80,17	650	816,3	3060	776,7
52	20,19	20,16	80,45	80,32	650	823,5	3055	781,2
53	20,15	20,15	80,42	80,43	650	830,3	3001	788,2
54	20,19	20,16	80,32	80,36	650	840,3	3138	797,6
55	20,24	20,14	80,46	80,19	650	840,4	3152	797,2
56	20,25	20,17	80,42	80,44	650	848,6	3099	803,2
57	20,2	20,15	80,48	80,46	650	838,4	3148	794,5
58	20,16	20,13	80,54	80,46	650	843,7	3084	800,4
59	20,22	20,2	80,3	80,46	650	843,1	3070	798,5
60	20,23	20,15	80,45	80,44	650	848,5	3162	803,7
61	20,17	20,16	80,52	80,23	650	840,9	3006	798,2
63	20,15	20,07	80,62	80,18	650	843	3128	802,1
64	20,12	20,1	80,4	80,34	650	830,4	3113	790,4
65	20,31	20,14	80,5	80,34	650	847,6	3094	801,7
66	20,21	20,14	80,49	80,42	650	858,1	3123	813,3
67	20,22	20,15	80,42	80,41	650	864	3182	818,9
68	20,17	20,15	80,61	80,33	650	872	3226	826,9

69	20,19	20,15	80,48	80,55	650	878,4	3118	832,1
70	20,17	20,18	80,48	80,51	650	871,7	3172	825,8
71	20,2	20,15	80,66	80,5	650	873,2	3152	826,3
72	20,17	20,32	80,38	80,34	650	867,6	3172	820,4
73	20,24	20,19	80,45	80,47	650	881,9	3221	834,2
74	20,23	20,17	80,48	80,55	650	879,3	3113	831,8

table 34 Dimensions, weight, density, dynamic frequency test specimen t=20mm w=80mm angle=(0°)

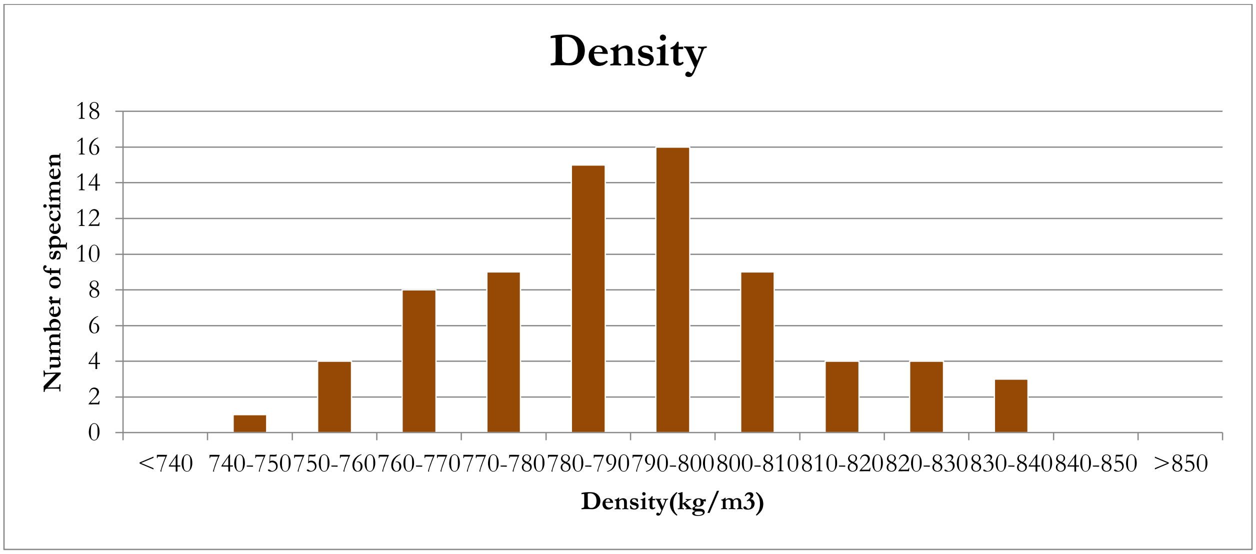


Figure 161 Density bar diagram for dimension 650x80x20

	Ttop (mm)	Tbot (mm)	Wtop (mm)	Wbot (mm)	Length (mm)	Weight (g)	Frequency (hZ)	Density (kg/m3)
1	20,1	20,26	170,04	170,03	651	1727,9	1674	773,5
2	20,22	20,15	170,15	170,32	651	1742,8	1635	779,1
3	20,17	20,25	170,6	170,15	651	1743,7	1654	777,9
4	20,24	20,13	170,12	170,14	651	1760,8	1635	787,6
5	20,22	20,19	170,19	170,19	651	1804,8	1615	806,2
6	20,36	20,14	170,34	170,32	651	1873,3	1688	834,3

table 35 Dimensions, weight, density, dynamic frequency test specimen t=20mm w=170mm angle=(45°)

	Ttop (mm)	Tbot (mm)	Wtop (mm)	Wbot (mm)	Length (mm)	Weight (g)	Frequency (hZ)	Density (kg/m3)
1	20,16	20,16	240,47	240,56	652	2513,5	2133	795,1
2	20,16	20,27	240,64	240,58	652	2519,1	2176	794,3
3	20,2	20,18	241,03	240,55	652	2507,4	2137	791,0
4	20,24	20,15	240,66	240,61	652	2587,2	2079	816,5
5	20,12	20,16	240,47	240,52	652	2516,5	2186	796,9
6	20,13	20,15	241,15	240,93	652	2476,2	2128	782,3

7	20,14	20,16	241,15	240,89	652	2461	2113	777,2
8	20,15	20,2	240,93	240,9	652	2465,7	2176	778,1
9	20,13	20,25	240,83	240,7	652	2451,8	2142	773,6
10	20,11	20,18	240,96	240,68	652	2438	2108	770,8
11	20,29	20,28	241,29	240,97	652	2402,7	2157	753,4
12	20,13	20,18	240,87	240,59	652	2431,9	2172	768,7
13	20,14	20,27	240,9	240,43	652	2445,4	2181	771,3
14	20,14	20,2	240,7	240,61	652	2492,8	2298	787,7
15	20,15	20,17	240,63	240,74	652	2489,8	2259	787,0
16	20,06	20,21	240,7	240,41	652	2434,7	2196	771,0
17	20,07	20,14	240,9	240,95	652	2445,9	2211	774,5
18	20,07	20,15	240,95	240,82	652	2485	2133	786,8
19	20,21	20,17	240,82	240,77	652	2517,6	2157	794,2
20	20,07	20,11	240,48	240,6	652	2526,7	2201	801,9
21	20,06	20,14	240,66	240,69	652	2510,7	2113	796,0
22	20,07	20,13	240,79	240,83	652	2467,5	2264	781,9
23	20,05	20,15	240,62	240,78	652	2464,4	2181	781,3
24	20,06	20,11	240,97	240,7	652	2476,2	2133	785,1
25	20,02	20,11	241,02	240,7	652	2438,7	2284	773,9
26	20,06	20,13	241,14	240,6	652	2385,9	2118	756,0
27	20,08	20,13	240,53	240,67	652	2384,7	2152	756,1
28	20,04	20,13	240,74	240,62	652	2390,1	2167	758,3
29	20,05	20,13	240,62	240,58	652	2444,9	2225	775,8
30	20,06	20,12	240,74	240,69	652	2433,1	2269	771,7
31	20,04	20,16	240,66	240,55	652	2436,3	2240	772,6
32	20,05	20,12	240,08	240,8	652	2427,9	2225	771,1
33	20,14	20,17	240,84	240,51	652	2498,5	2289	790,0
34	20,15	20,17	239,36	241,78	652	2498	2303	790,0

table 36 Dimensions, weight, density, dynamic frequency test specimen t=20mm w=240mm angle=(90°)

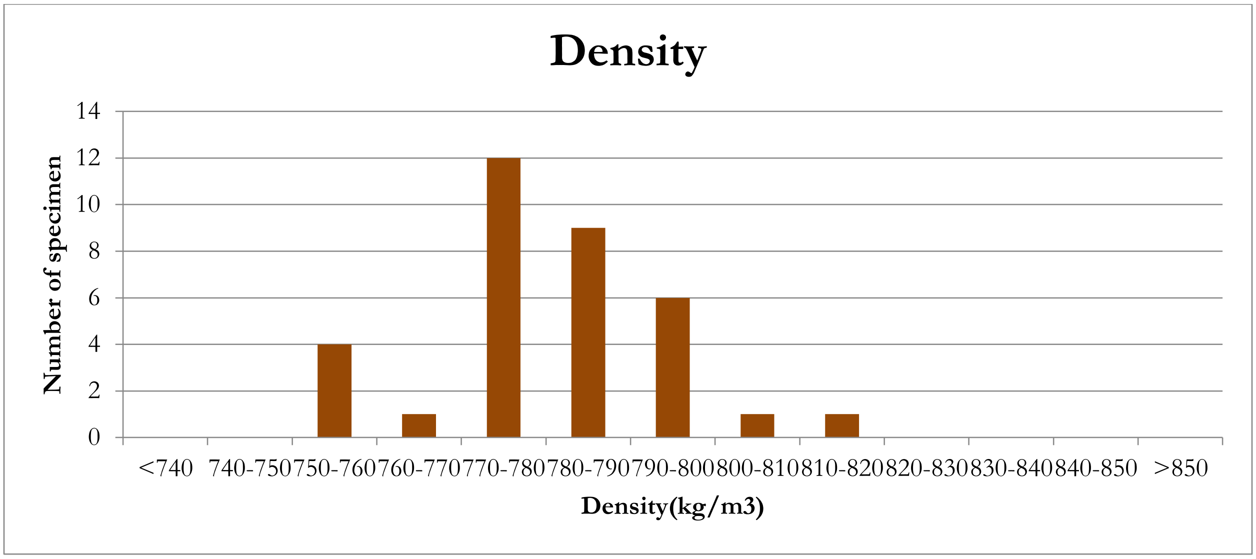


Figure 162 diagram for dimension 650x240x20

	Ttop (mm)	Tbot (mm)	Wtop (mm)	Wbot (mm)	Length (mm)	Weight (g)	Frequency (hZ)	Density (kg/m3)
1	39,7	39,73	81,59	81,79	651	1719,4	3392	814,1
2	39,72	39,74	81,33	81,16	651	1712,8	3450	815,1
3	39,75	39,77	81,15	81,75	651	1706,5	3338	809,4
4	39,74	39,75	81,21	81,01	651	1708,2	3401	814,0
5	39,9	39,75	81,18	80,93	650	1686,8	3431	803,9
6	39,76	39,77	81,43	81,73	650	1726	3509	818,5
7	39,79	39,75	81,06	81,22	650	1721,4	3479	820,7
8	39,78	39,78	81,25	81,34	650	1700,7	3484	809,1
9	39,78	39,76	81,18	81,23	650	1668	3431	794,6
10	39,8	39,76	81,21	80,82	650	1673,8	3445	799,0
11	39,80	39,76	81,49	81,51	650	1746,8	3421	828,9
12	39,76	39,75	81,24	81,22	650	1720	3382	819,4
13	39,81	39,76	81,43	81,29	650	1697	3387	806,6
14	39,82	39,8	81,36	81,09	650	1686,2	3406	802,3
15	39,8	39,77	81,48	80,82	650	1696,6	3377	808,5

table 37 Dimensions, weight, density, dynamic frequency test specimen t=40mm w=80mm angle=(0°)

	Ttop (mm)	Tbot (mm)	Wtop (mm)	Wbot (mm)	Length (mm)	Weight (g)	Frequency (hZ)	Density (kg/m3)
1	39,66	39,62	241,48	241,32	651	5115	1620	821,1
2	39,67	39,6	241,47	241,25	651	5090	1698	817,3
3	39,69	39,7	241,02	241,12	651	5035	1645	808,2
4	39,68	39,62	241,2	241,18	651	5040	1654	809,6
5	39,72	39,63	241,32	241,4	651	5030	1649	806,9
6	39,73	39,65	240,97	240,94	651	5030	1669	807,9
7	39,74	39,59	241,02	240,99	652	5110	1645	819,9
8	39,73	39,64	241,34	241,19	652	5090	1688	815,4
9	39,73	39,65	241,24	241,14	652	5060	1693	810,7
10	39,76	39,72	241,3	241,14	652	5055	1654	808,8
11	39,74	39,69	241,38	240,99	652	5030	1664	805,4
12	39,78	39,86	241,25	241,1	652	5050	1645	806,5

table 38 Dimensions, weight, density, dynamic frequency test specimen t=40mm w=240mm angle=(90°)

13.1.2 Codenames and sorting

See Figure 163 and Figure 164 for the location where the specimen number is located on the LVL-Q plate.

Density(kg/m^3)	Specimen number	code
762,5	20	T20_A0_N1_1a
762,7	25	T20_A0_N1_1b
774,8	30	T20_A0_N1_2a
775,0	10	T20_A0_N1_2b
783,5	43	T20_A0_N1_3a
785,1	14	T20_A0_N1_3b
792,0	42	T20_A0_N1_4a
792,2	41	T20_A0_N1_4b
800,4	58	T20_A0_N1_5a
801,7	65	T20_A0_N1_5b
Average density	783,0	kg/m^3

table 39 Codenames for test specimen N= sorted on density, for dimensions 650x80x20(length x width x thickness)

Density(kg/m^3)	specimen	code
763,8	29	T20_A0_N2_1a
765,0	9	T20_A0_N2_1b
776,1	27	T20_A0_N2_2a
776,7	51	T20_A0_N2_2b
785,2	33	T20_A0_N2_3a
786,5	11	T20_A0_N2_3b
792,9	2	T20_A0_N2_4a
793,1	45	T20_A0_N2_4b
802,1	63	T20_A0_N2_5a
802,3	49	T20_A0_N2_5b
Average density	784,4	kg/m^3

table 40 Codenames for test specimen N=2 sorted on density, for dimensions 650x80x20(length x width x thickness)

Density(kg/m^3)	specimen	code
766,7	7	T20_A0_N3_1a
767,7	21	T20_A0_N3_1b
778,9	36	T20_A0_N3_2a
780,3	38	T20_A0_N3_2b
787,5	4	T20_A0_N3_3a
788,2	53	T20_A0_N3_3b
793,1	44	T20_A0_N3_4a
794,5	57	T20_A0_N3_4b
802,4	18	T20_A0_N3_5a
802,9	48	T20_A0_N3_5b
Average density	786,2	kg/m^3

table 41 Codenames for test specimen N=3 sorted on density, for dimensions 650x80x20(length x width x thickness)

Density(kg/m^3)	specimen	code
768,9	28	T20_A0_N1R_1a
769,5	50	T20_A0_N1R_1b
780,8	15	T20_A0_N1R_2a
780,9	13	T20_A0_N1R_2b
788,3	35	T20_A0_N1R_3a
789,7	39	T20_A0_N1R_3b
794,8	5	T20_A0_N1R_4a
795,3	12	T20_A0_N1R_4b
803,2	56	T20_A0_N1R_5a
803,7	60	T20_A0_N1R_5b
Average density	787,5	kg/m^3

table 42 Codenames for test specimen N=2(R) sorted on density, for dimensions 650x80x20(length x width x thickness)

Density(kg/m^3)	specimen	code
772,1	23	T20_A0_N2R_1a
773,1	8	T20_A0_N2R_1b
781,2	52	T20_A0_N2R_2a
781,3	34	T20_A0_N2R_2b
790,4	64	T20_A0_N2R_3a
790,8	3	T20_A0_N2R_3b
797,2	55	T20_A0_N2R_4a
797,6	54	T20_A0_N2R_4b
804,9	46	T20_A0_N2R_5a
812,1	47	T20_A0_N2R_5b
Average density	790,1	kg/m^3

table 43 Codenames for test specimen N=1(R) sorted on density, for dimensions 650x80x20(length x width x thickness)

Density(kg/m^3)	specimen	Code
773,2	32	T20_A0_N3R_1a
774,1	37	T20_A0_N3R_1b
782,9	24	T20_A0_N3R_2a
783,5	17	T20_A0_N3R_2b
791,2	40	T20_A0_N3R_3a
791,9	1	T20_A0_N3R_3b
798,2	61	T20_A0_N3R_4a
798,5	59	T20_A0_N3R_4b
813,3	6	T20_A0_N3R_5a
813,3	66	T20_A0_N3R_5b
Average density	792,0	kg/m^3

table 44 Codenames for test specimen N=3R) sorted on density, for dimensions 650x80x20(length x width x thickness)

Density(kg/m^3)	specimen	code
773,5	1	T20_A45_N1_1a
779,1	2	T20_A45_N1_1b
777,9	3	T20_A45_N1_2a
787,6	4	T20_A45_N1_2b
806,2	5	T20_A45_N1_3a
834,3	6	T20_A45_N1_3b
Average density	793,1	kg/m^3

table 45 Codenames for test specimen N=1 sorted on density, for dimensions 650x170x20(length x width x thickness)

Density(kg/m^3)	specimen	code
758,3	28	T20_A90_N1_1a
768,7	12	T20_A90_N1_1b
771,7	30	T20_A90_N1_2a
772,6	31	T20_A90_N1_2b
777,2	7	T20_A90_N1_3a
778,1	8	T20_A90_N1_3b
786,8	18	T20_A90_N1_4a
787,0	15	T20_A90_N1_4b
794,2	19	T20_A90_N1_5a
794,3	2	T20_A90_N1_5b
Average density	778,9	kg/m^3

table 46 Codenames for test specimen N=1) sorted on density, for dimensions 650x240x20(length x width x thickness)

Density(kg/m^3)	specimen	code
770,8	10	T20_A90_N2_1a
771,0	16	T20_A90_N2_1b
773,6	9	T20_A90_N2_2a
773,9	25	T20_A90_N2_2b
781,3	23	T20_A90_N2_3a
781,9	22	T20_A90_N2_3b
787,7	14	T20_A90_N2_4a
790,0	34	T20_A90_N2_4b
795,1	1	T20_A90_N2_5a
796,0	21	T20_A90_N2_5b
Average density	782,1	kg/m^3

table 47 Codenames for test specimen N=2 sorted on density, for dimensions 650x240x20(length x width x thickness)

Density(kg/m^3)	specimen	code
771,1	32	T20_A90_N3_1a
771,3	13	T20_A90_N3_1b
774,5	17	T20_A90_N3_2a
775,8	29	T20_A90_N3_2b
782,3	6	T20_A90_N3_3a
785,1	24	T20_A90_N3_3b
790,0	33	T20_A90_N3_4a
791,0	3	T20_A90_N3_4b
796,9	5	T20_A90_N3_5a
801,9	20	T20_A90_N3_5b
Average density	784,0	kg/m^3

table 48 Codenames for test specimen N=3 sorted on density, for dimensions 650x240x20(length x width x thickness)

Density(kg/m^3)	specimen	code
802,3	14	T40_A0_N1_1a
806,6	13	T40_A0_N1_1b
814,1	1	T40_A0_N1_2a
815,1	2	T40_A0_N1_2b
Average density	809,5	kg/m^3

table 49 Codenames for test specimen N=1 sorted on density, for dimensions 650x80x40(length x width x thickness)

Density(kg/m^3)	specimen	code
808,5	15	T40_A0_N2_1a
809,1	8	T40_A0_N2_1b
818,5	6	T40_A0_N2_2a
819,4	12	T40_A0_N2_2b
Average density	813,9	kg/m^3

table 50 Codenames for test specimen N=2 sorted on density, for dimensions 650x80x40(length x width x thickness)

Density(kg/m^3)	specimen	code
809,4	3	T40_A0_N3_1a
814,0	4	T40_A0_N3_1b
820,7	7	T40_A0_N3_2a
828,9	11	T40_A0_N3_2b
Average density	818,2	kg/m^3

table 51 Codenames for test specimen N=3 sorted on density, for dimensions 650x80x40(length x width x thickness)

Density(kg/m^3)	specimen	code
805,4	11	T40_A90_N1_1a
806,5	12	T40_A90_N1_1b
809,6	4	T40_A90_N1_2a
810,7	9	T40_A90_N1_2b
Average density	808,0	kg/m^3

table 52 Codenames for test specimen N=1 sorted on density, for dimensions 650x240x40(length x width x thickness)

Density(kg/m^3)	specimen	code
806,9	5	T40_A90_N2_1a
807,9	6	T40_A90_N2_1b
815,4	8	T40_A90_N2_2a
817,3	2	T40_A90_N2_2b
Average density	811,9	kg/m^3

table 53 Codenames for test specimen N=2 sorted on density, for dimensions 650x240x40(length x width x thickness)

Density(kg/m^3)	specimen	code
808,2	3	T40_A90_N3_1a
808,8	10	T40_A90_N3_1b
819,9	7	T40_A90_N3_2a
821,1	1	T40_A90_N3_2b
Average density	814,5	kg/m^3

table 54 Codenames for test specimen N=3 sorted on density, for dimensions 650x240x40(length x width x thickness)

13.1.3 Saw location(drawing)

Saw drawings of 20mm plate and 40mm plate. The 20mm plate was probably a few cm's longer than ordered as specimen 32 and 34 are outside the drawing. The dimensions however are correct.

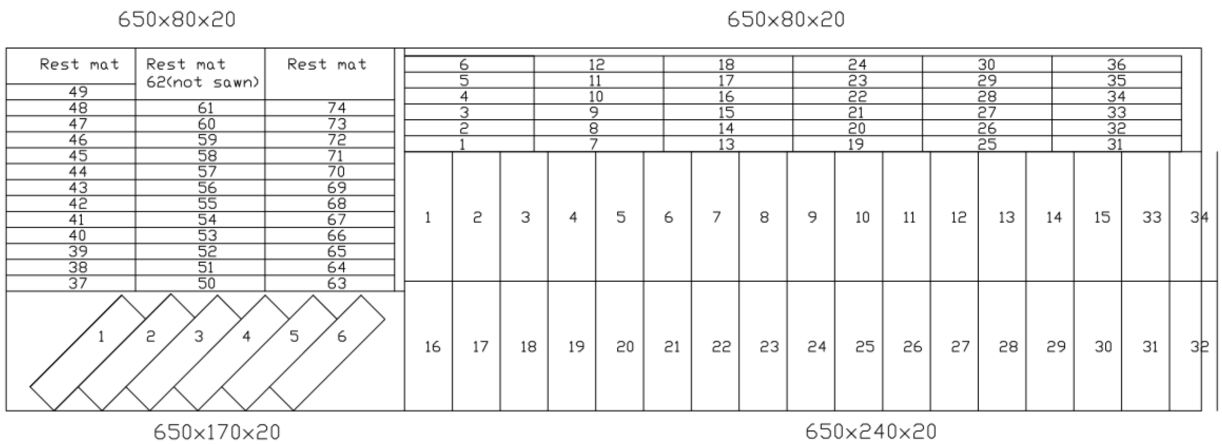


Figure 163 Saw location/order plate 20mm

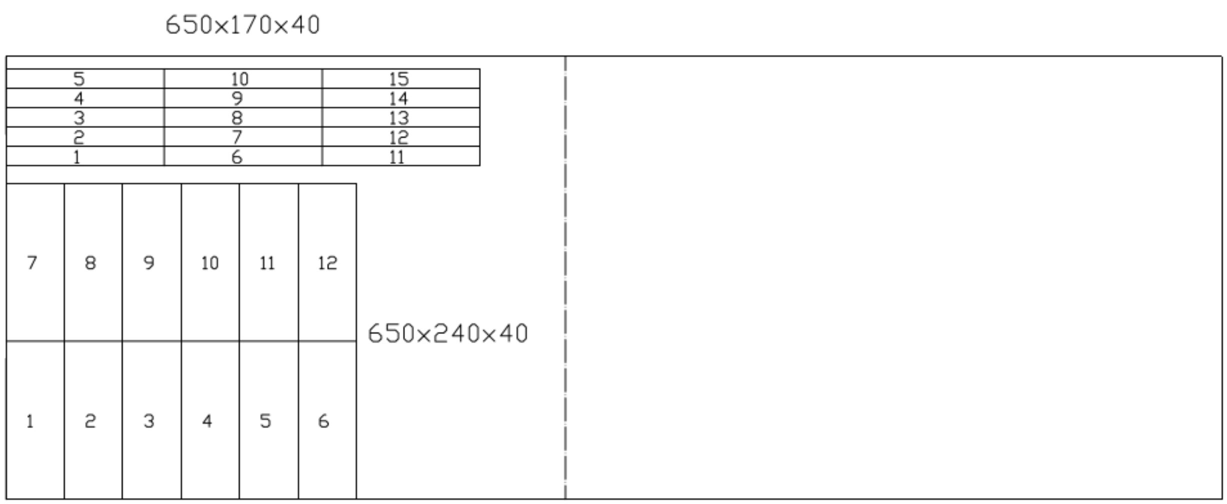
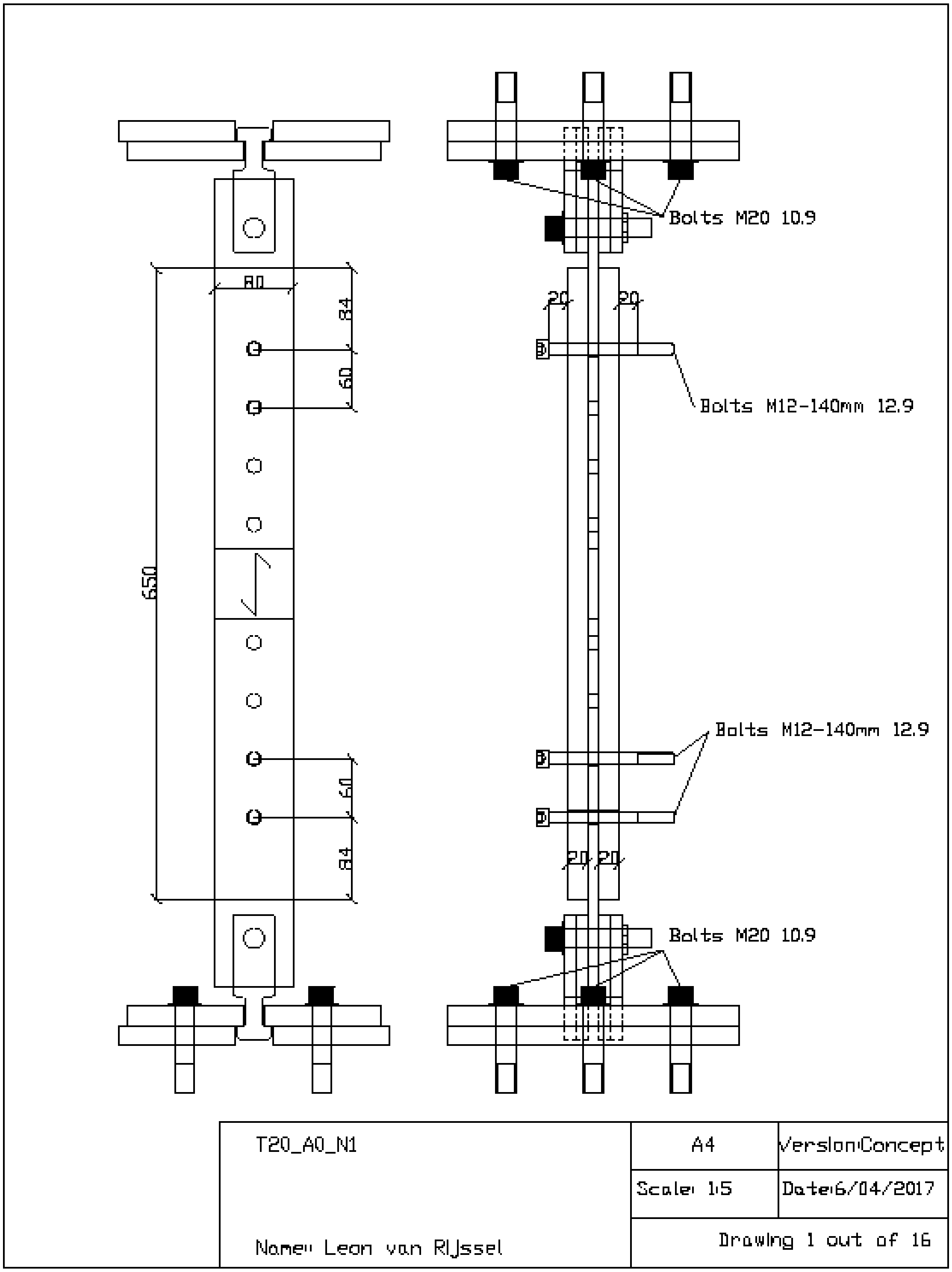
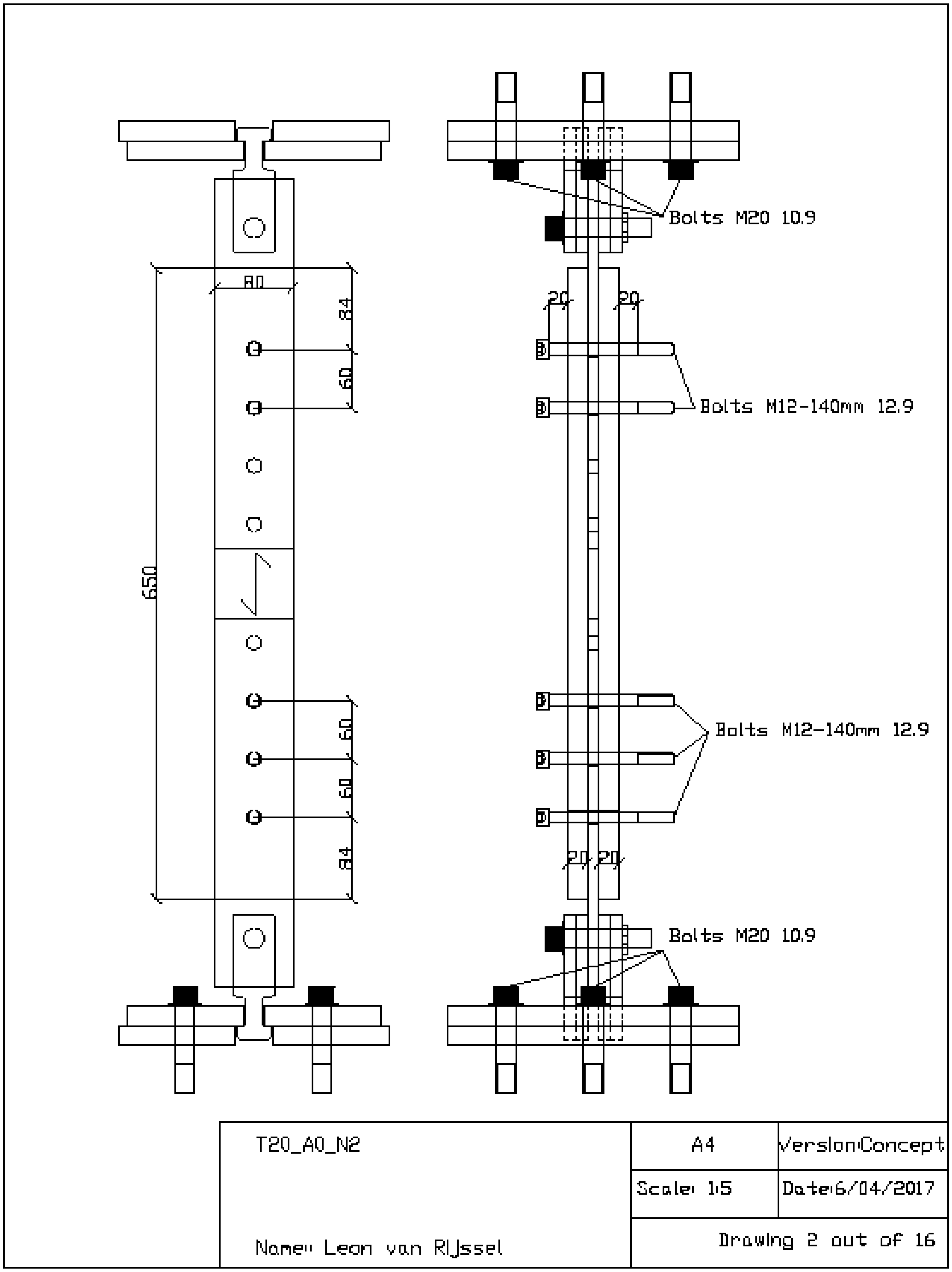
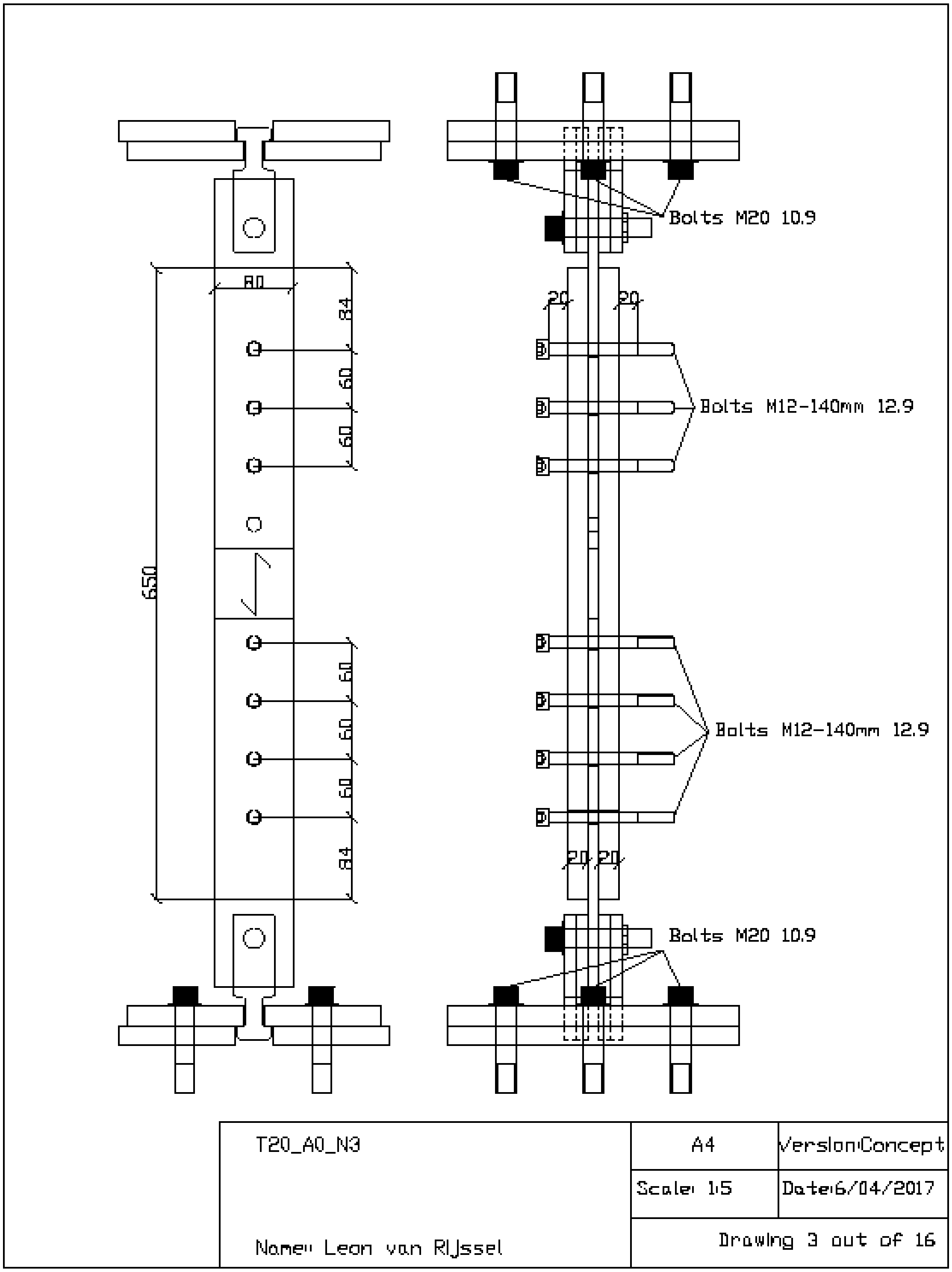


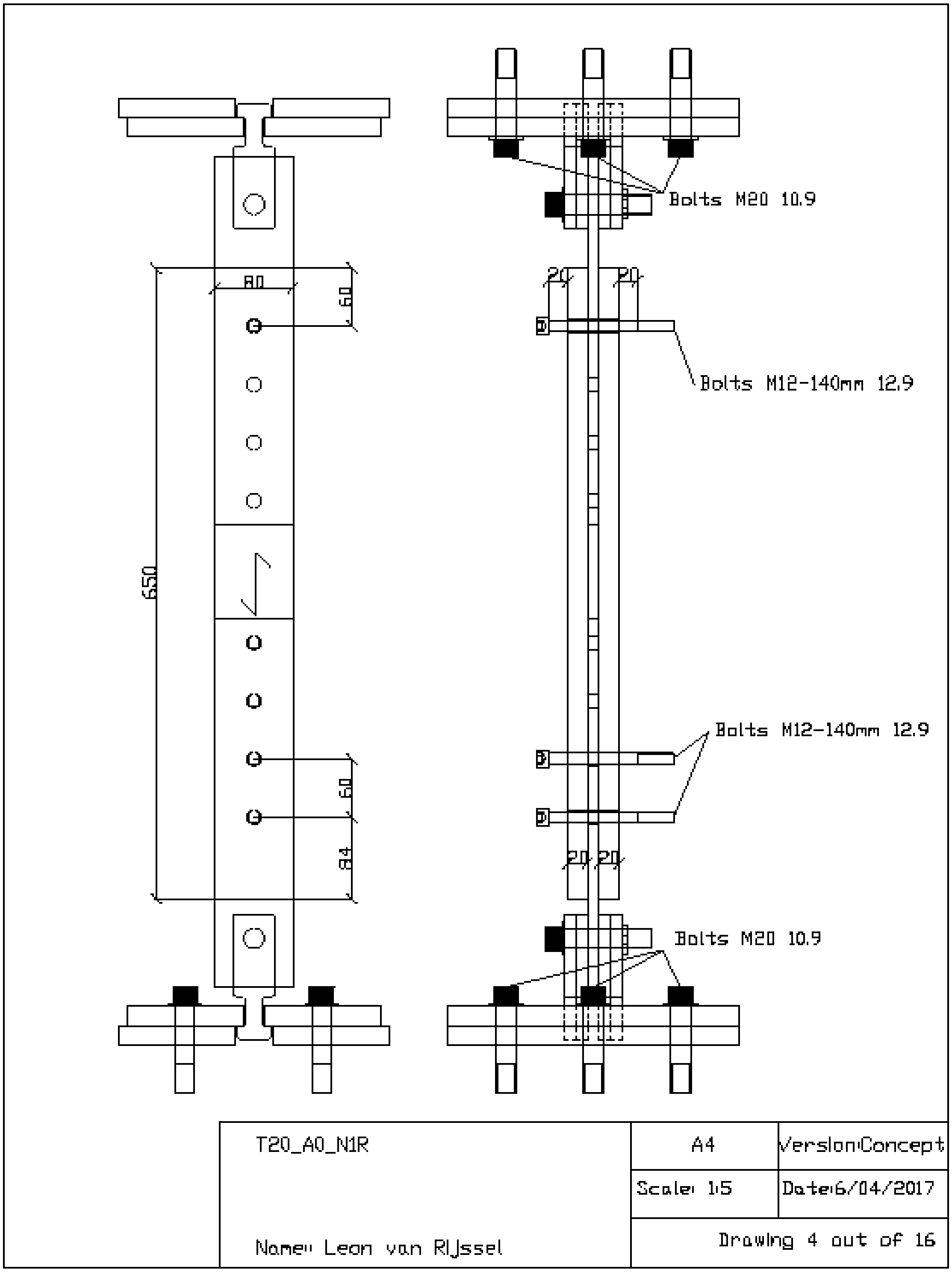
Figure 164 Saw location/order plate 40mm

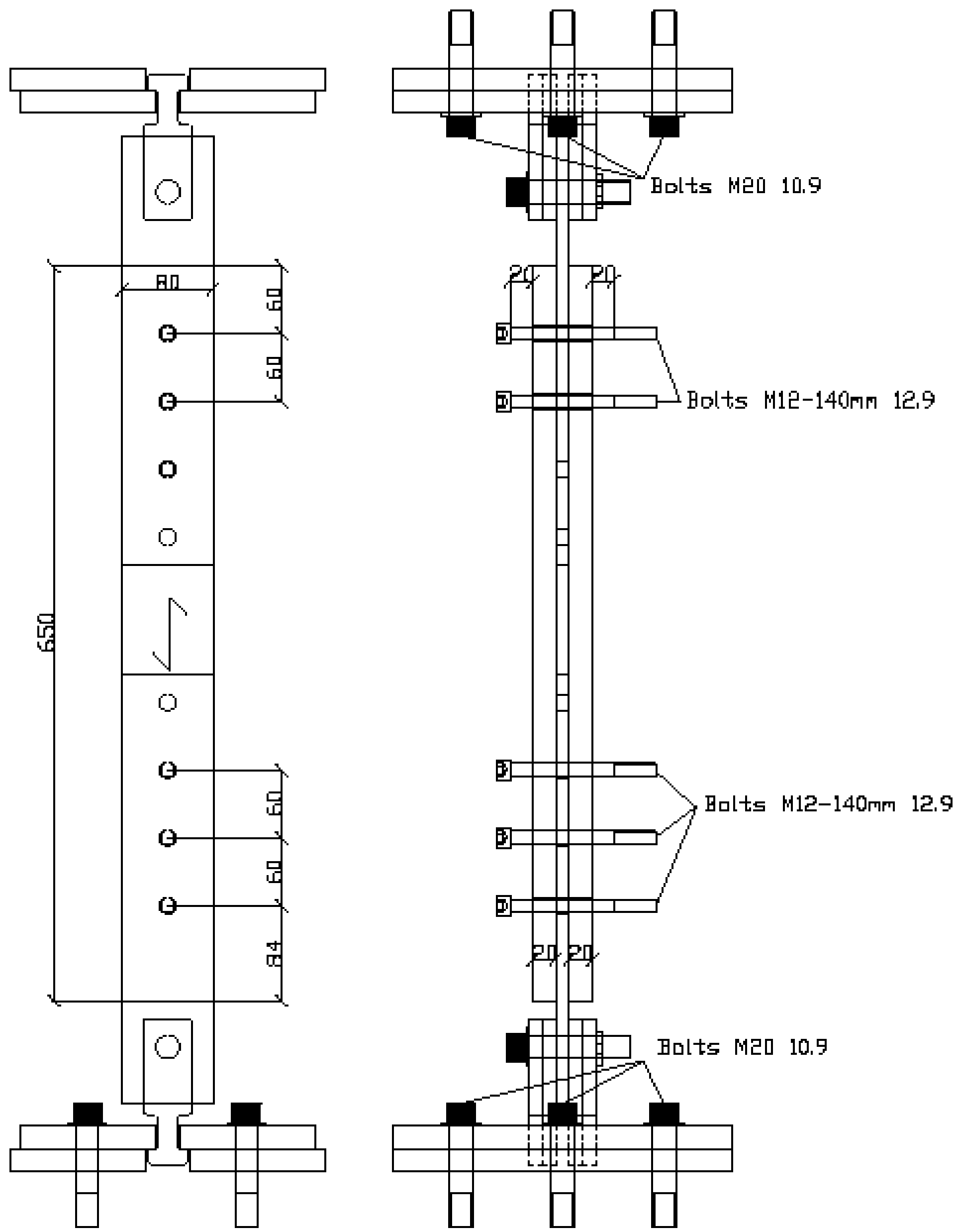
13.1.4 Drawings test specimen



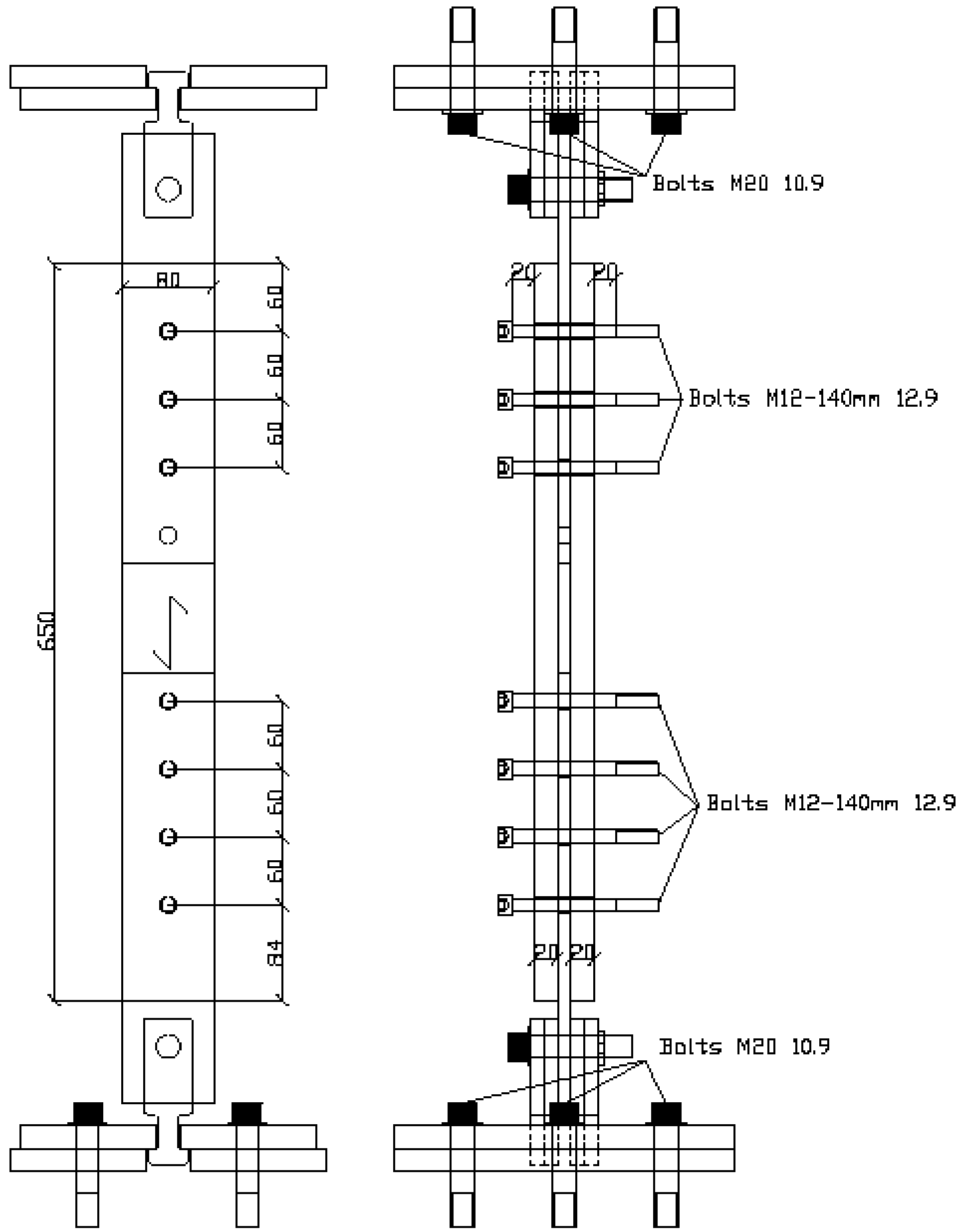

Bolts M20 10.9
80
20
20
84
60
Bolts M12-140mm 12.9
650
60
60
Bolts M12-140mm 12.9
84
20 20
Bolts M20 10.9
T20_A0_N2
A4
Version:Concept
Scale: 1:5
Date:6/04/2017
Name: Leon van Rijssel
Drawing 2 out of 16


Bolts M20 10.9
80
84
60
60
650
20
20
Bolts M12-140mm 12.9
60
60
60
84
Bolts M12-140mm 12.9
20
20
Bolts M20 10.9
T20_A0_N3
A4
Version:Concept
Scale: 1:5
Date:6/04/2017
Name: Leon van Rijssel
Drawing 3 out of 16

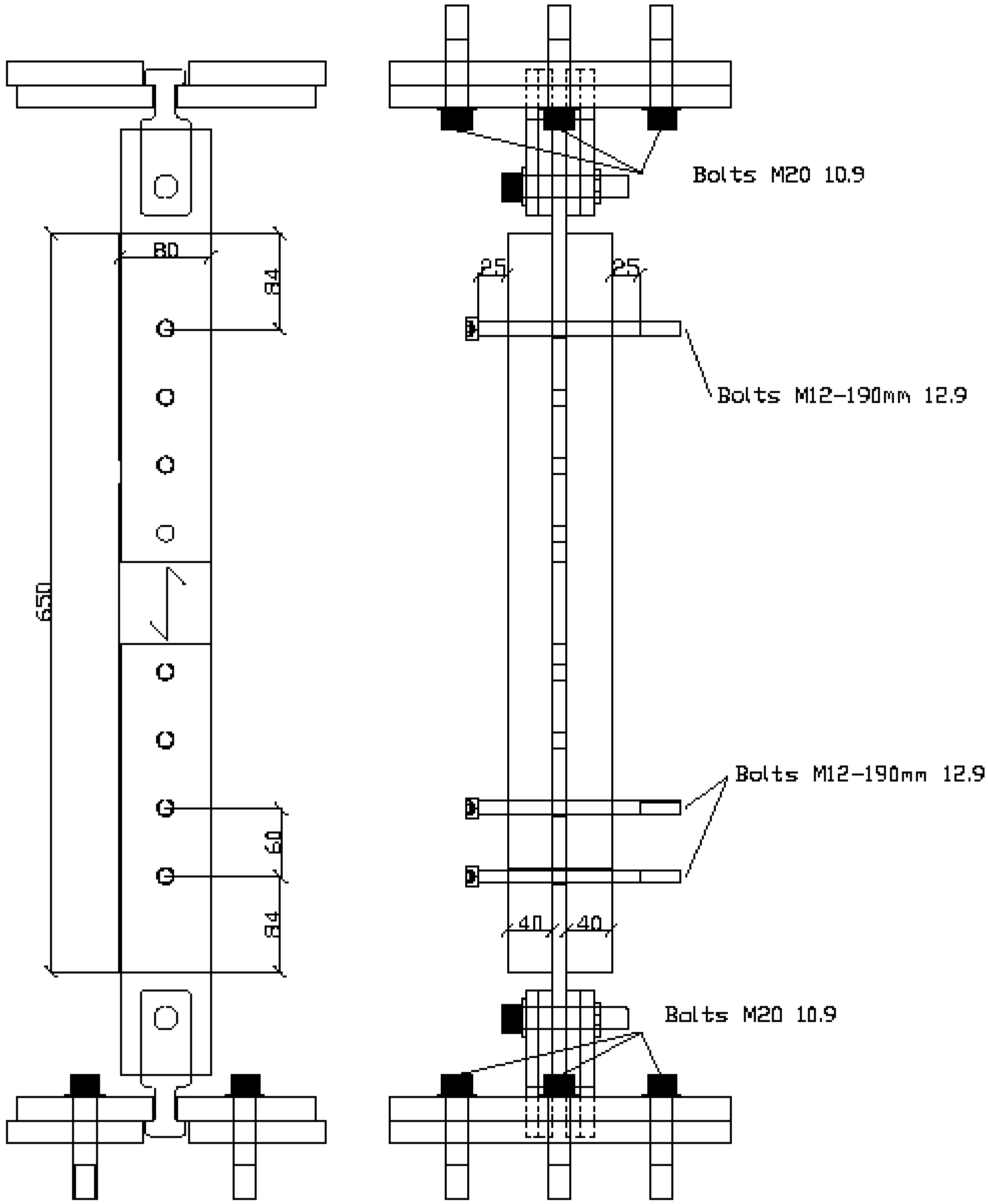

Bolts M20 10.9
80
60
20
20
Bolts M12-140mm 12.9
650
Bolts M12-140mm 12.9
60
84
20
20
Bolts M20 10.9
T20_A0_N1R
A4
Version:Concept
Scale: 1:5
Date:6/04/2017
Name: Leon van Rijssel
Drawing 4 out of 16



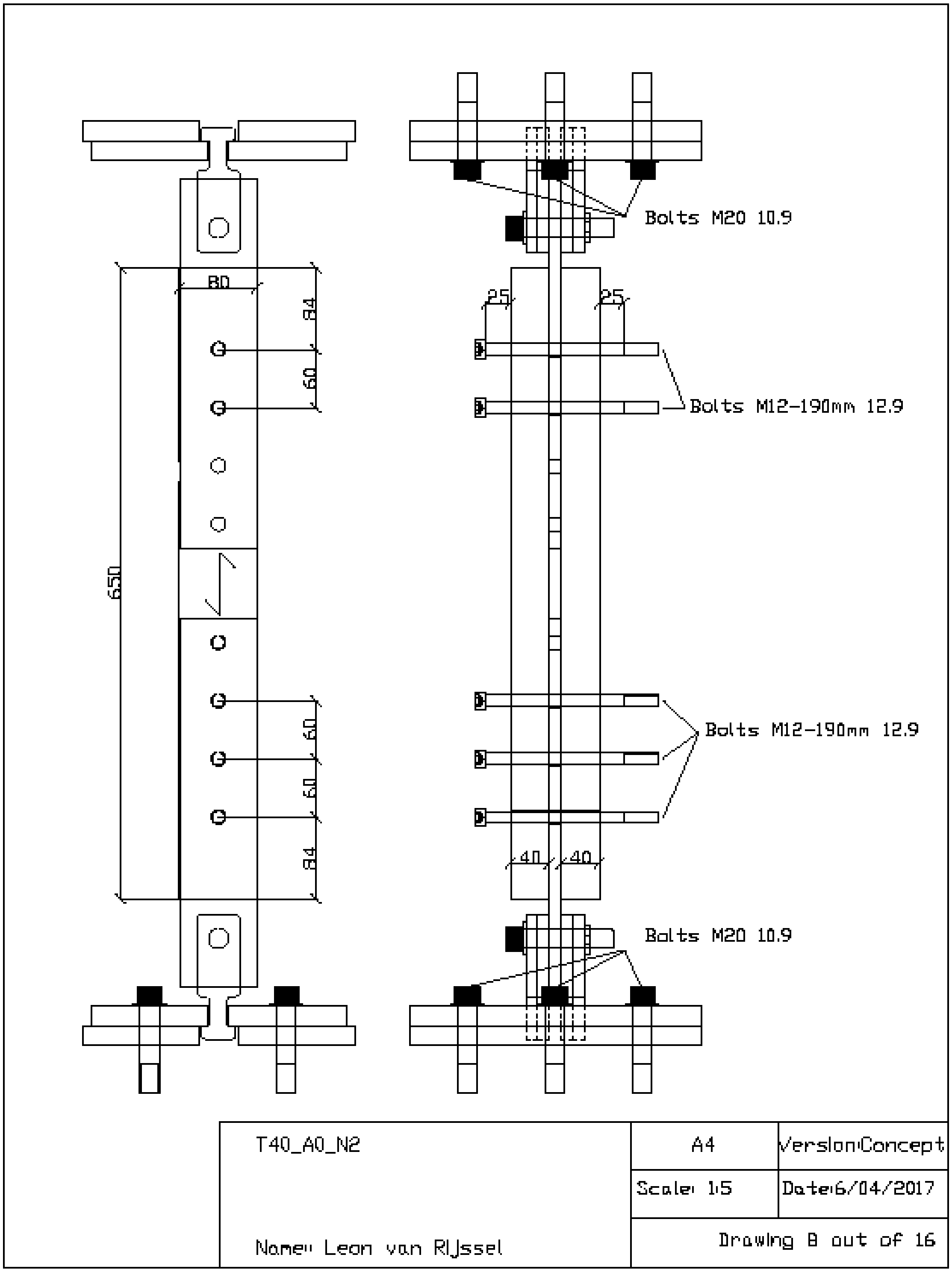
T20_A0_N2R	A4	Version:Concept
	Scale: 1:5	Date:6/04/2017
Name: Leon van Rijssel	Drawing 5 out of 16	

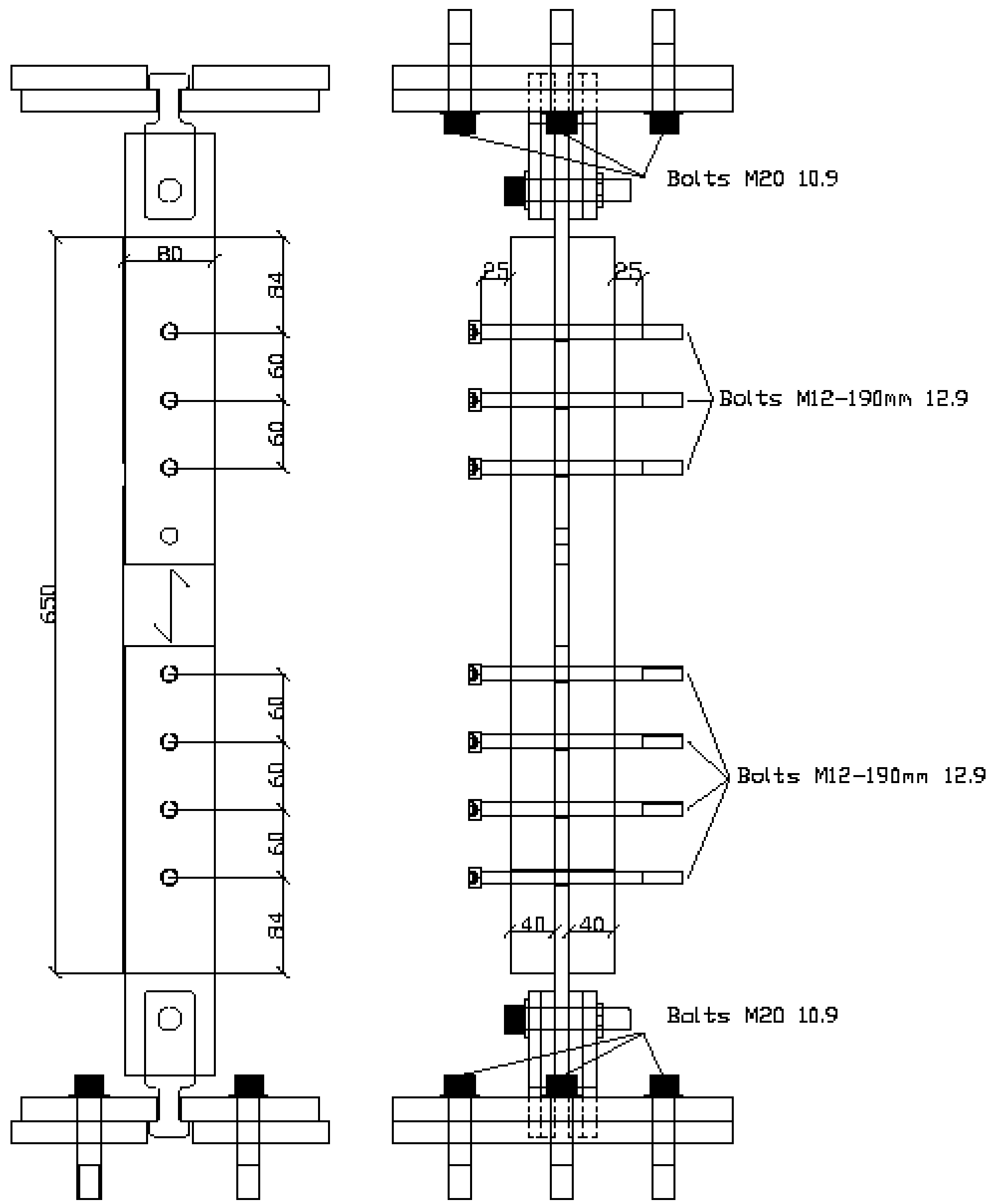


T20_A0_N3R	A4	Version:Concept
	Scale: 1:5	Date:6/04/2017
Name: Leon van Rijssel	Drawing 6 out of 16	

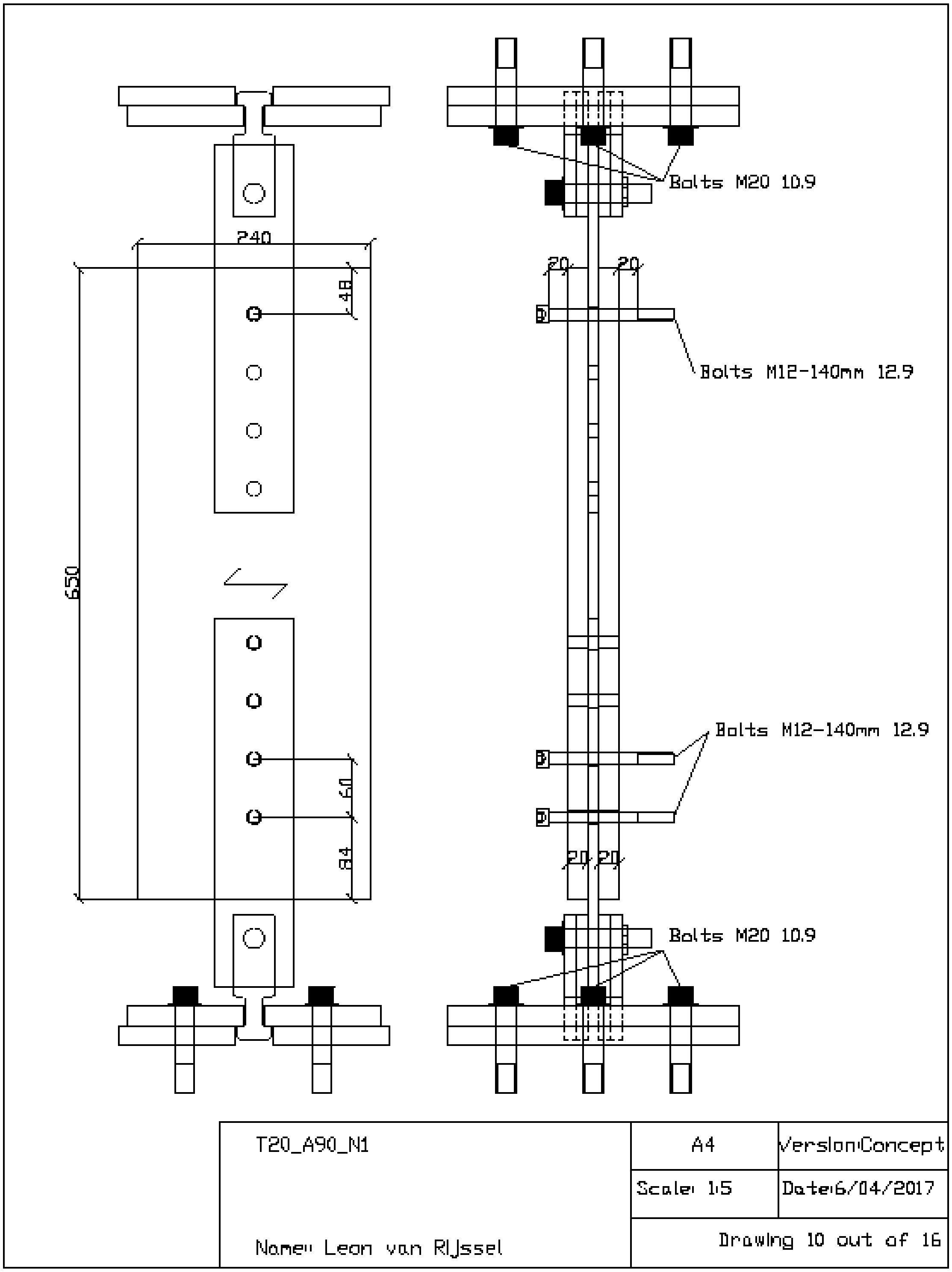


T40_A0_N1	A4	Version:Concept
	Scale: 1:5	Date:6/04/2017
Name: Leon van Rijssel	Drawing 7 out of 16	

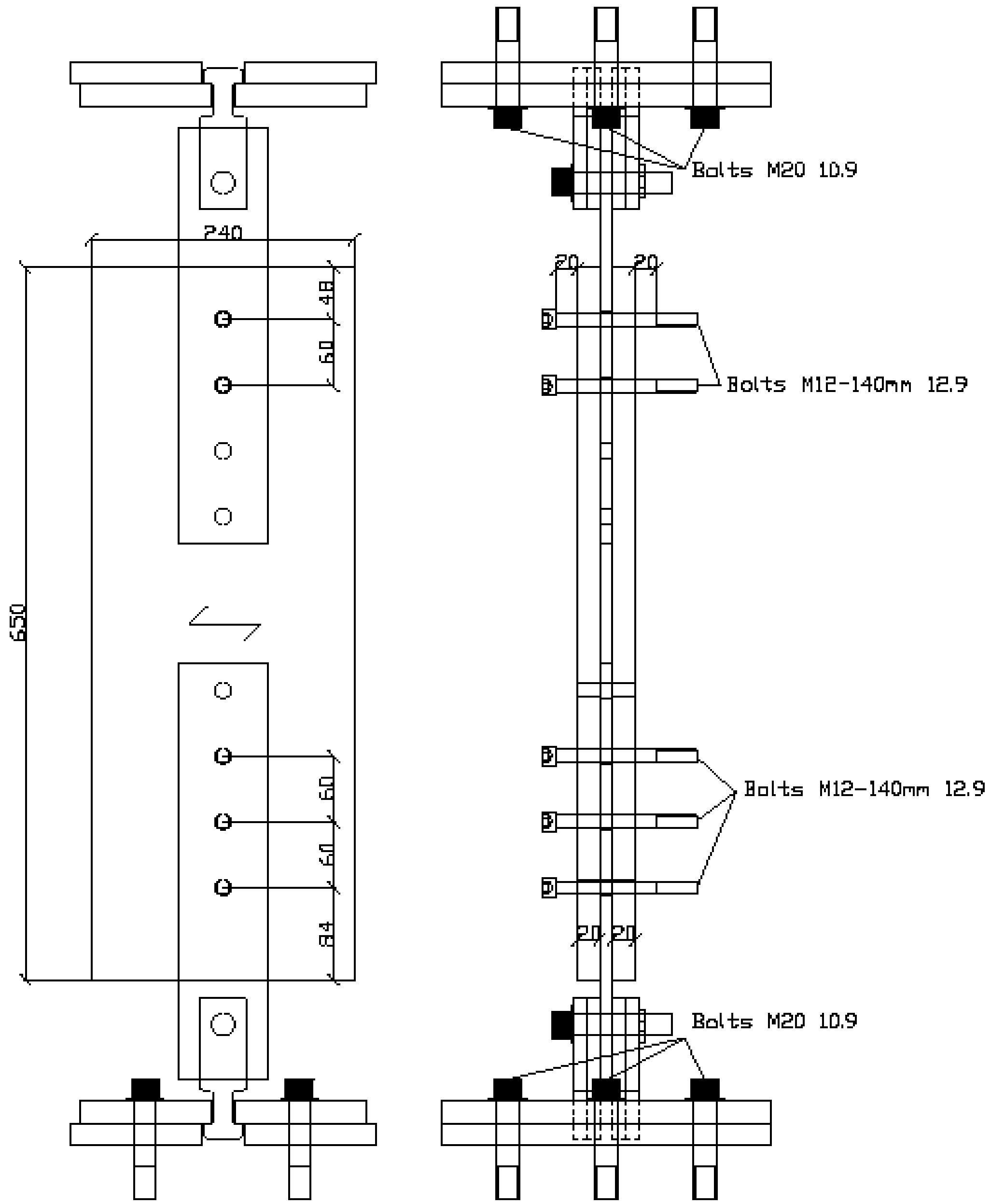

Bolts M20 10.9
80
84
60
25
25
Bolts M12-190mm 12.9
650
Bolts M12-190mm 12.9
60
60
84
40
40
Bolts M20 10.9
T40_A0_N2
A4
Version:Concept
Scale: 1:5
Date:6/04/2017
Name: Leon van Rijssel
Drawing 8 out of 16



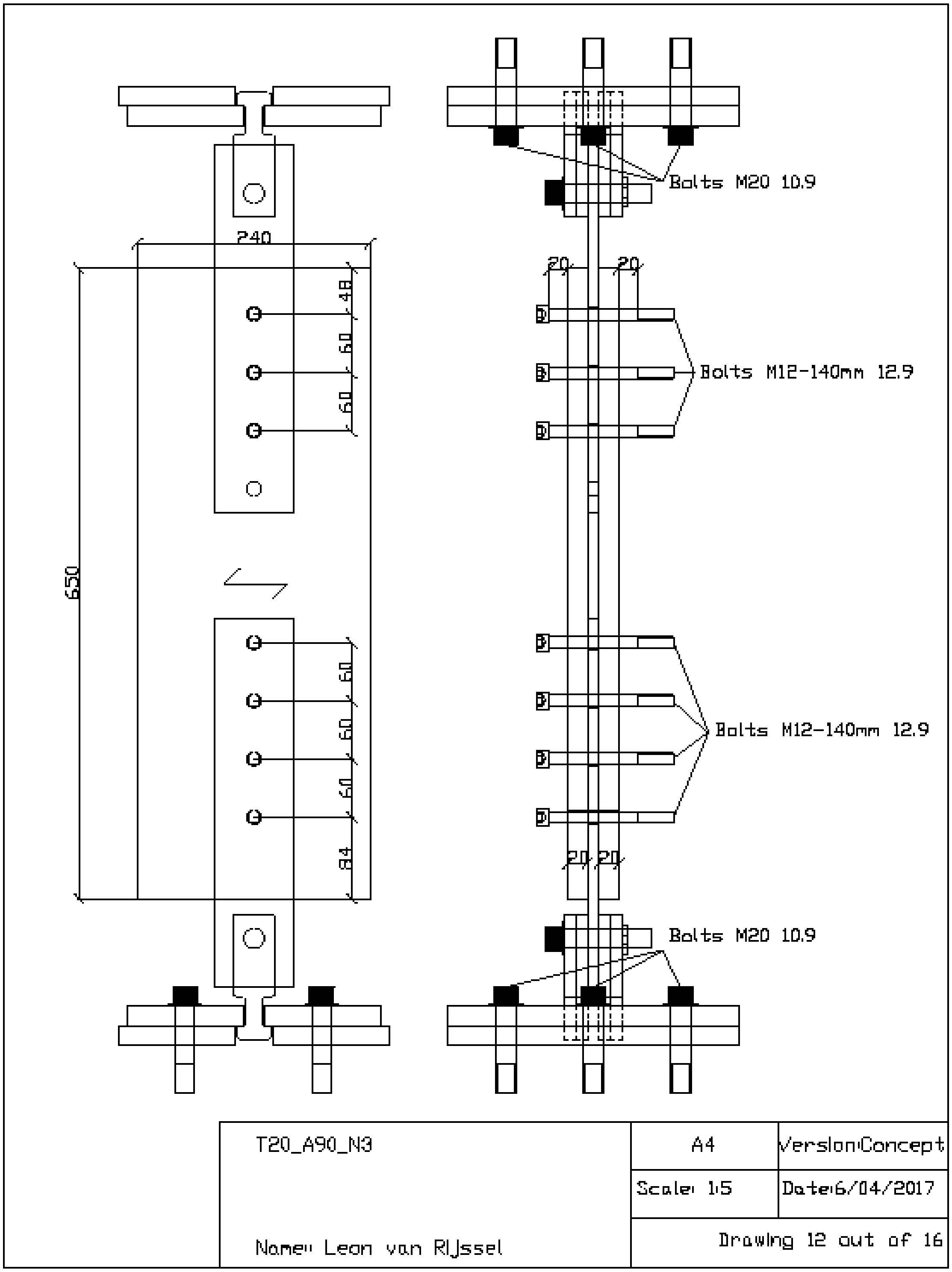
T40_A0_N3	A4	Version:Concept
	Scale: 1:5	Date:6/04/2017
Name: Leon van Rijssel	Drawing 9 out of 16	

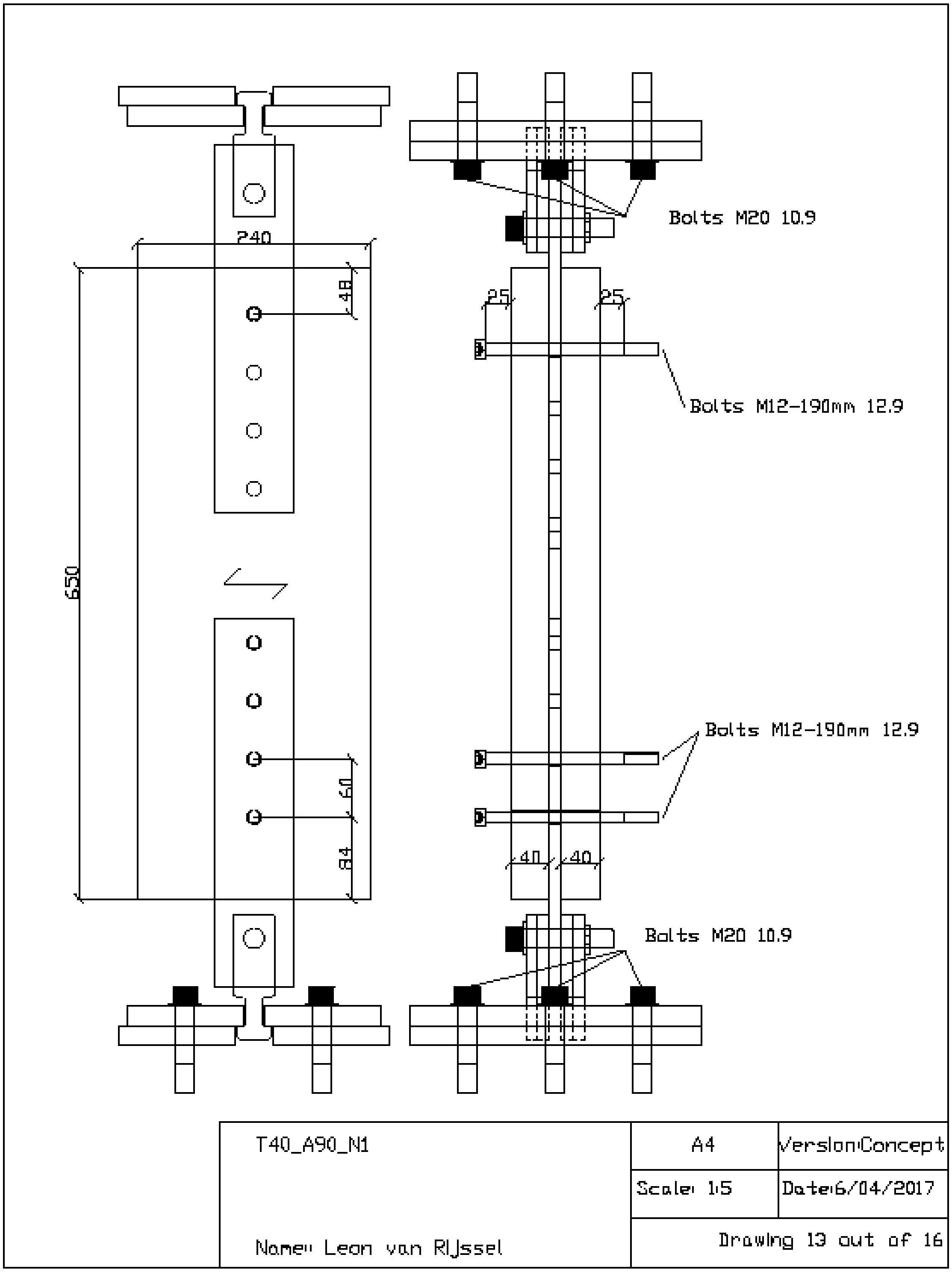


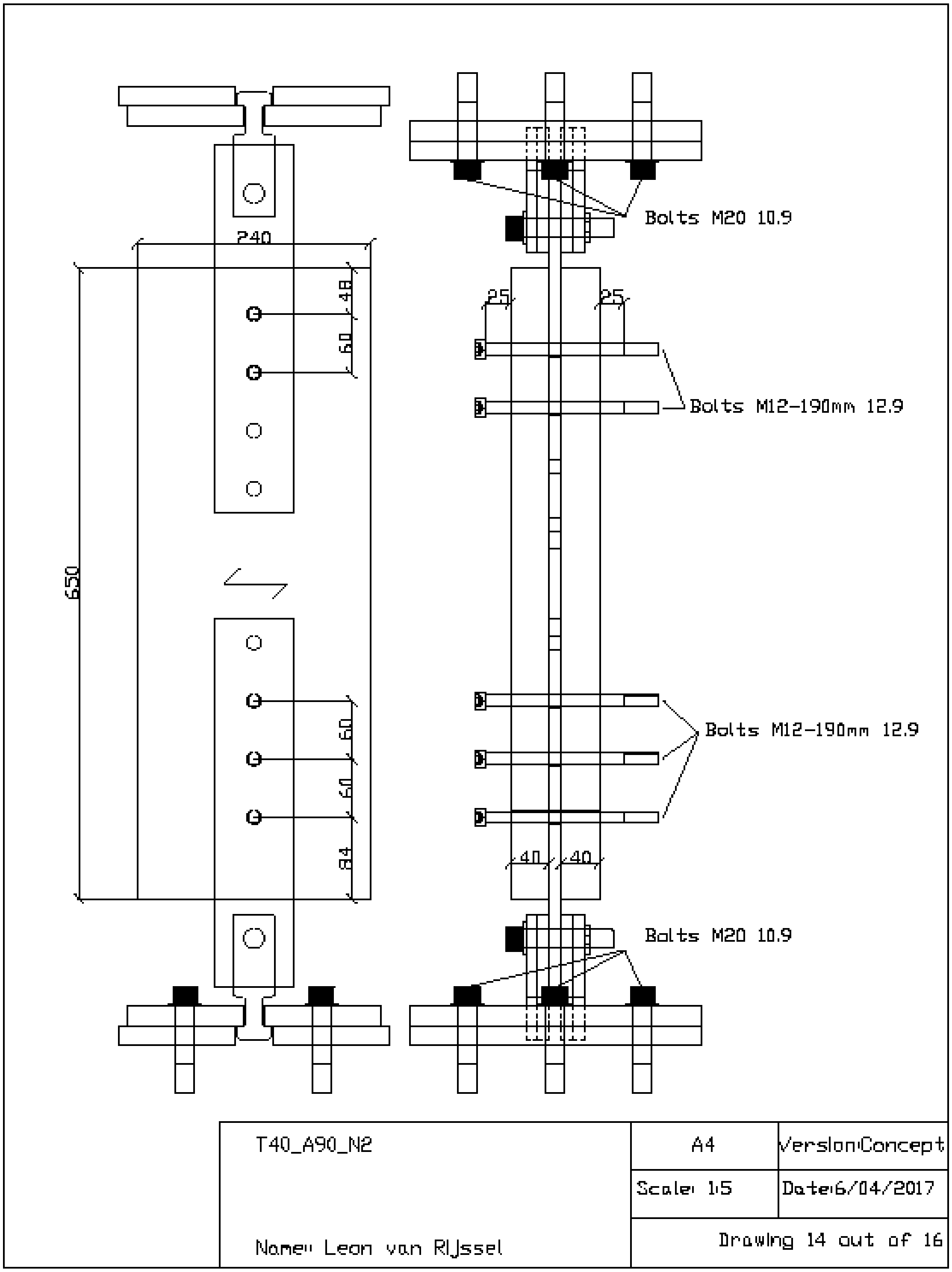
240
48
650
60
84
20
20
20
20
Bolts M20 10.9
Bolts M12-140mm 12.9
Bolts M12-140mm 12.9
Bolts M20 10.9
T20_A90_N1
A4
Version:Concept
Scale: 1:5
Date:6/04/2017
Name: Leon van Rijssel
Drawing 10 out of 16

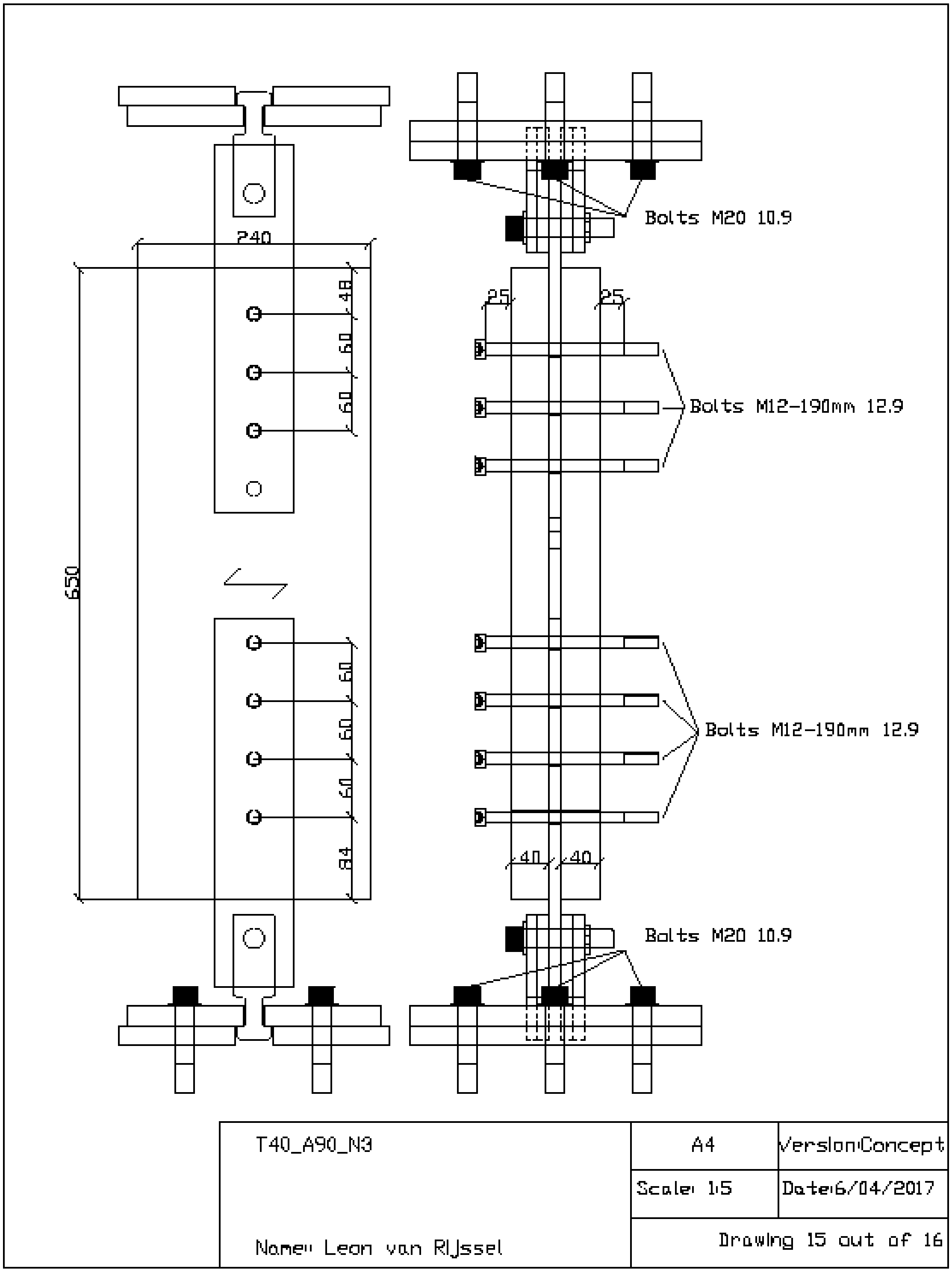


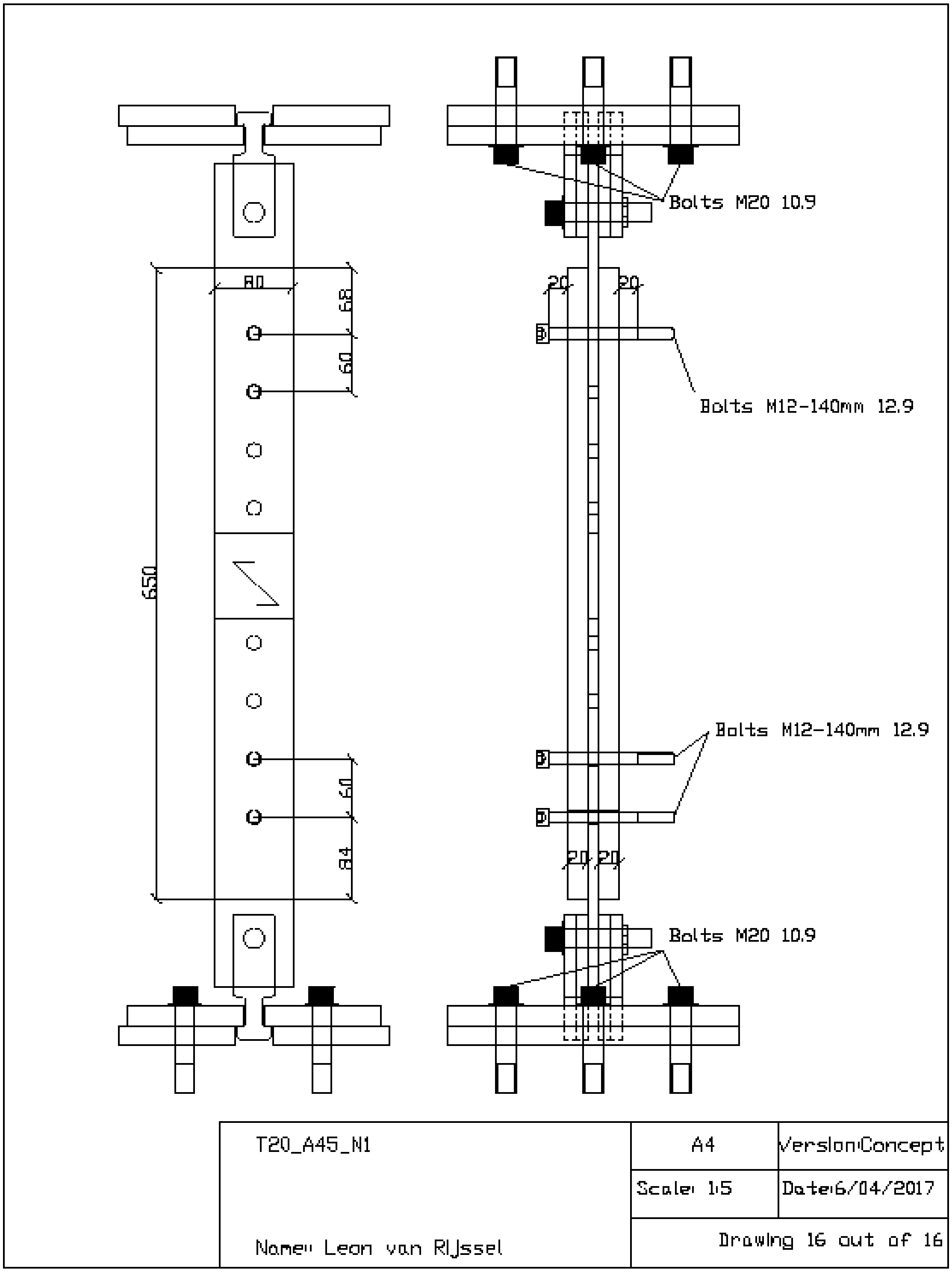
T20_A90_N2	A4	Version:Concept
	Scale: 1:5	Date:6/04/2017
Name: Leon van Rijssel	Drawing 11 out of 16	


240
48
60
60
650
60
60
60
84
Bolts M20 10.9
20
20
Bolts M12-140mm 12.9
Bolts M12-140mm 12.9
20 20
Bolts M20 10.9
T20_A90_N3
A4
Version:Concept
Scale: 1:5
Date:6/04/2017
Name: Leon van Rijssel
Drawing 12 out of 16


240
48
650
60
84
25
25
40
40
Bolts M20 10.9
Bolts M12-190mm 12.9
Bolts M12-190mm 12.9
Bolts M20 10.9
T40_A90_N1
A4
Version:Concept
Scale: 1:5
Date:6/04/2017
Name: Leon van RIJssel
Drawing 13 out of 16


240
48
60
650
60
60
84
25
25
Bolts M20 10.9
Bolts M12-190mm 12.9
Bolts M12-190mm 12.9
40
40
Bolts M20 10.9
T40_A90_N2
A4
Version:Concept
Scale: 1:5
Date:6/04/2017
Name: Leon van Rijssel
Drawing 14 out of 16


Bolts M20 10.9
240
25
25
48
60
60
Bolts M12-190mm 12.9
650
60
60
60
84
Bolts M12-190mm 12.9
40
40
Bolts M20 10.9
T40_A90_N3
A4
Version:Concept
Scale: 1:5
Date:6/04/2017
Drawing 15 out of 16
Name: Leon van Rijssel


Bolts M20 10.9
80
68
60
650
20
20
Bolts M12-140mm 12.9
Bolts M12-140mm 12.9
60
84
20
20
Bolts M20 10.9
T20_A45_N1
A4
Version:Concept
Scale: 1:5
Date:6/04/2017
Name: Leon van Rijssel
Drawing 16 out of 16

13.1.5 Baubuche-Q product information

Table 3: Characteristic strength and stiffness values in N/mm² and density in kg/m³

Type of load		Board BauBuche S Laminated veneer lumber "Beech LVL with longitudinal layers"	Board BauBuche Q Laminated veneer lumber "Beech LVL with crosswise layers"	
Nominal thickness in mm		$20 \leq B \leq 80$	20 [a)]	$30 \leq B \leq 80$
Strength values				
Flatwise bending				
Bending	$f_{m,0,flat,k}$	80	70	75
	$f_{m,90,flat,k}$		32	20
Compressive	$f_{c,90,flat,k}$	10 [c)]	13 [c)]	
Shear	$f_{v,0,flat,k}$	8	3,8	
Edgewise bending				
Bending[b)]	$f_{m,0,edge,k}$	75	54	60
	$f_{m,90,edge,k}$		18	10
Tensile ∥ to the grain	$f_{t,0}$	60	45	51
Tensile ⊥ to the grain	$f_{t,90,edge,k}$	1,5	16	8
Compressive ∥ to the grain	$f_{c,0,k}$	57,5 [c)]	45,6 [c)]	53,3 [c)]
Compressive ⊥ to the grain	$f_{c,90,edge,k}$	14	37 [c)]	19 [c)]
Shear	$f_{v,0,edge,k}$	8	7,8	

Stiffness values				
Modulus of elasticity	$E_{0,mean}$	16800	11800	13200
Modulus of elasticity	$E_{0,05}$	14900	10900	12200
Modulus of elasticity	$E_{90,mean}$	470	3900	2200
Modulus of elasticity	$E_{90,05}$	400		
Shear modulus edgewise	$G_{v,0,edge,mean}$	760	820	
Shear modulus flatwise	$G_{v,0,flat,mean}$	850	430	
density				
Mean density	ρ_{mean}	800		
Char. density	ρ_k	730		

a) "Beech LVL with crosswise layers" with a nominal thickness of 20 mm according to Annex 2 must not be used in edge bending.

b) Values apply for H ≤ 300 mm. For 300 < H ≤ 1000 mm, the characteristic strength value must be multiplied by the factor $k_h = (300/h)^{0.12}$. H is the dimension of the overall cross-section in mm, which is decisive for the bending stress.

c) If used in service class 1, the compressive strength can be increased by the factor 1.2.

13.2 T20_A0_N1

***Before Testing*(pictures test specimen T20_A0_N1_4 embedment failure):**

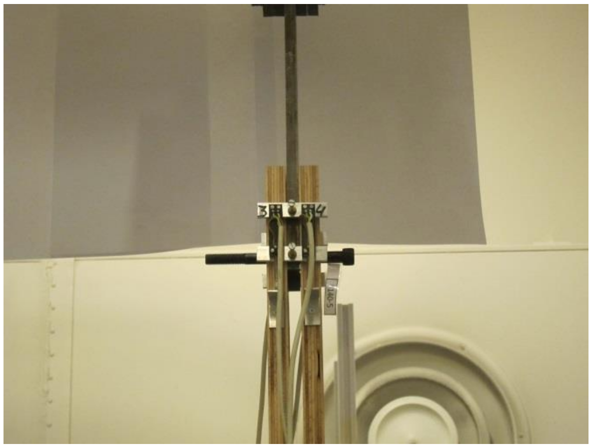


Figure 165 Front view

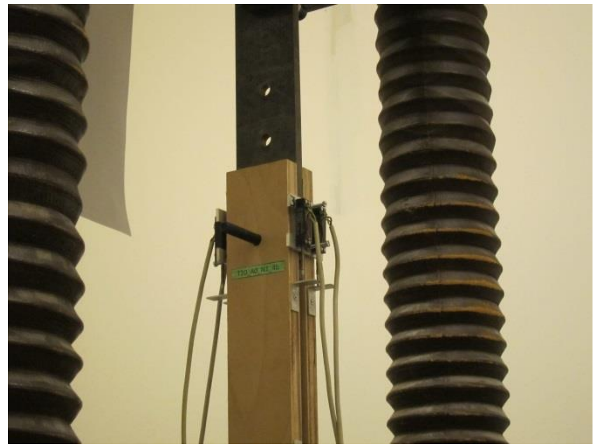


Figure 166 Perspective view nr. 1

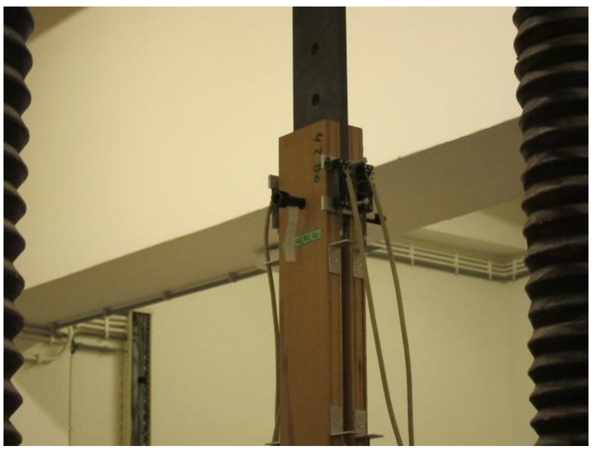


Figure 167 Perspective view nr 2

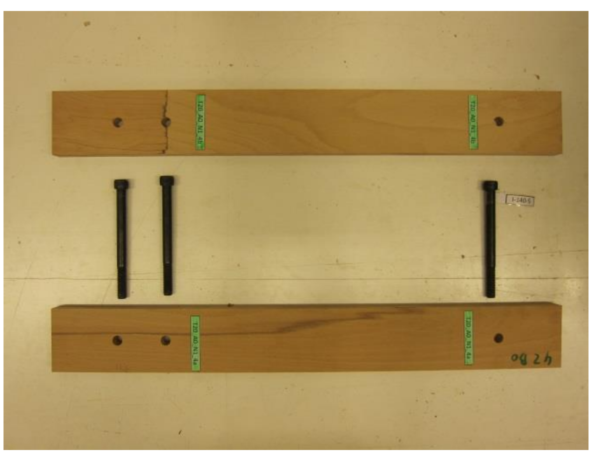


Figure 168 Overview materials

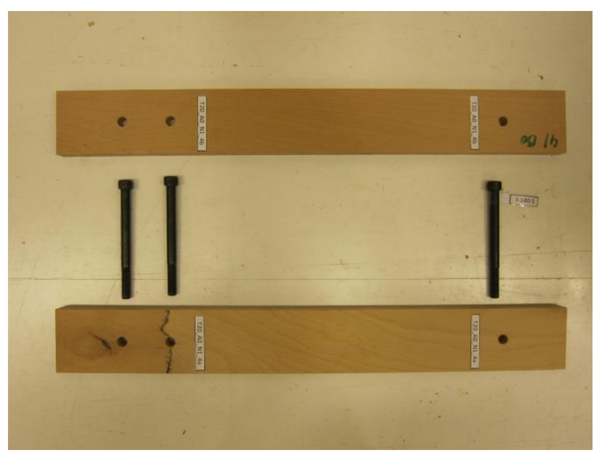


Figure 169 Overview materials

After testing

Figure 170 Front view

Figure 171 Perspective view nr. 1

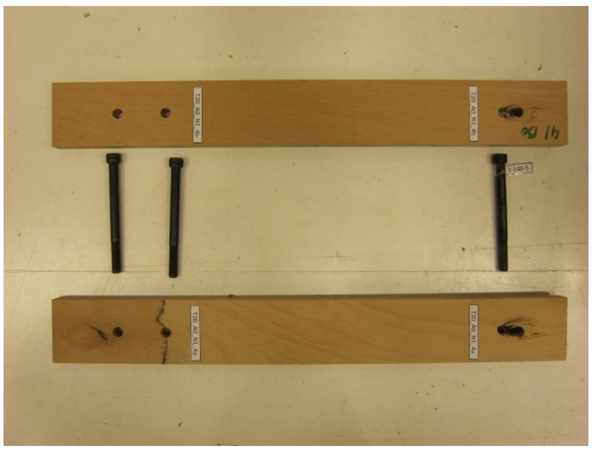


Figure 172 Overview materials

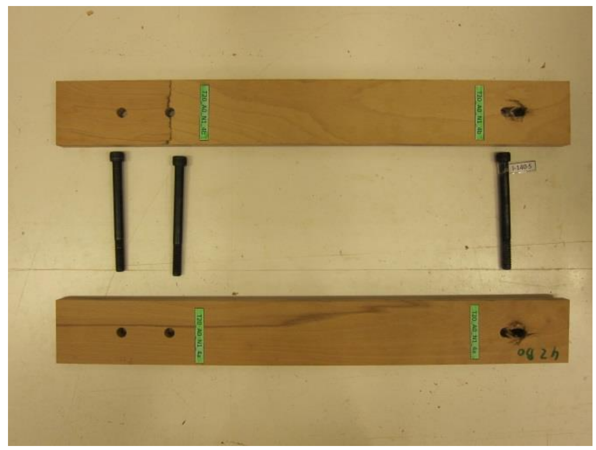


Figure 173 Overview materials

Figure 174 Closeup failure(Surface towards steel plate)

Figure 176 Closeup failure(Surface on the outside)

Figure 175 Closeup failure(Surface towards steel plate))

Figure 177 Closeup failure(Surface on the outside)

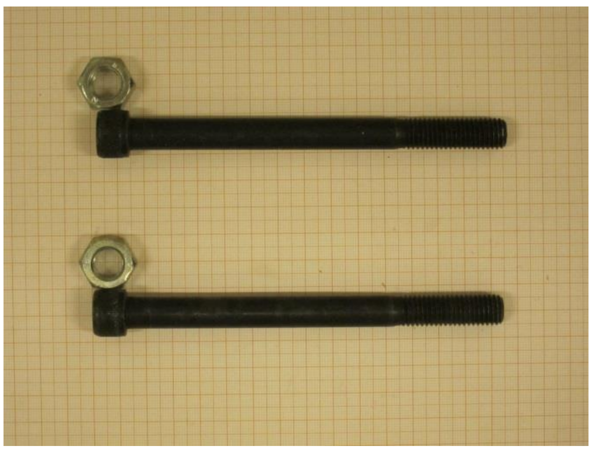


Figure 178 Dowels after testing strengthened side

Figure 179 Dowels after testing test side

13.2.1 T20_A0_N1_1

Material coding:

Labels Timber	T20_A0_N1_1a	T20_A0_N1_1b
Labels Steel Test side	I-140-2	
Labels Steel Strengthened. side	New	New

Table 55 Material coding T20_A0_N1_1

Log:

Material: *Large voids present in both cross sections.(not present at the location of the dowel)*

F_{est}: *50kN*
Displacement controlled speed(1): *0,02mm/s*
Displacement controlled speed(2): *0.04*

During testing: *First official test, the load plateau at 0,4 F_{est} was kept for 14 seconds longer due to a mistake(inexpierence). At 0,7 Fest the load was kept at a rate of 0,02mm per second which was increased to 0,04 after 13min as the loading of the test was too long.*

Cause of failure: *embedment failure*

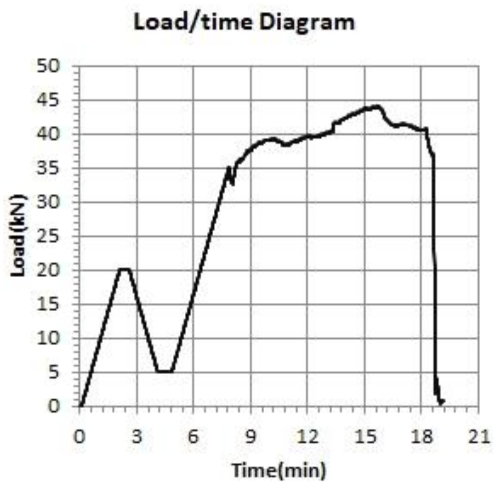
Additional remarks: *Test has been halted around 20mm displacement*

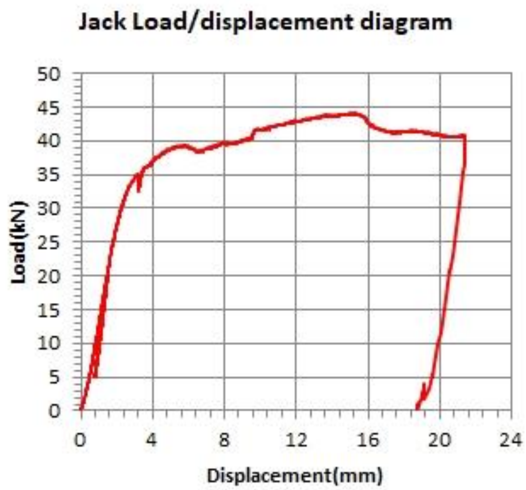
Figure 180 Perspective view nr1. After testing

Data:

T20_A0_N1_1	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	40,39	7,68	0,74	9,42	13,23
$F_{0,5}$	38,55	5,00	0,71	6,70	10,96
$F_{failure}$	-	-	-	-	-

Table 56 Results of specimen T20_A0_N1_1





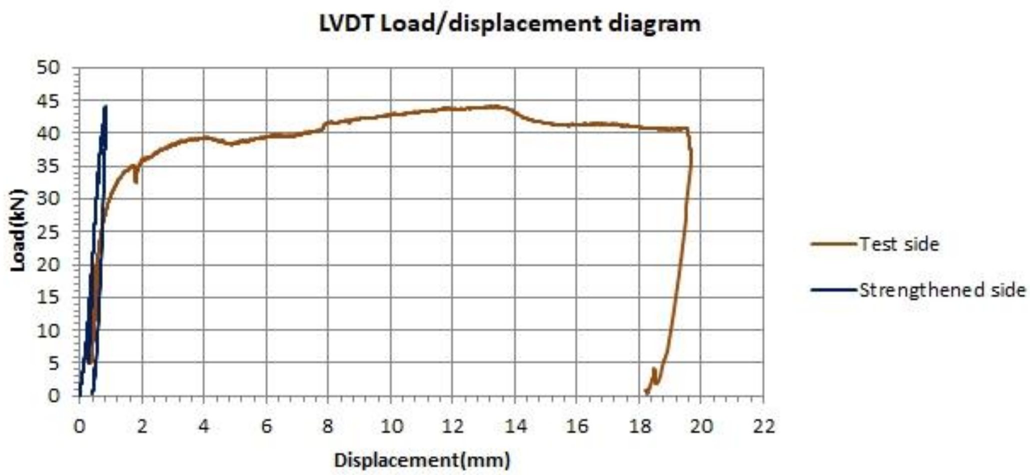


Figure 181 Graphical results of T20_A0_N1_1

13.2.2 *T20_A0_N1_2*

Material coding:

T20_A0_N1_2	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	48,40	7,52	1,02	10,10	13,54
$F_{0,5}$	44,70	5,00	0,95	7,47	11,35
$F_{failure}$	-	-	-	-	-

Table 57 Material coding T20_A0_N1_2

Log:

Material: *Minor void located in specimen A, no further important defects*

F_{est}:*50kN*
Displacement controlled speed(1): *0,02mm/s*
Displacement controlled speed(2): *0.04*

During testing: Procedure went according to guidelines.

Cause of failure: *embedment failure*

Additional remarks: *Test has been halted around 20mm displacement*

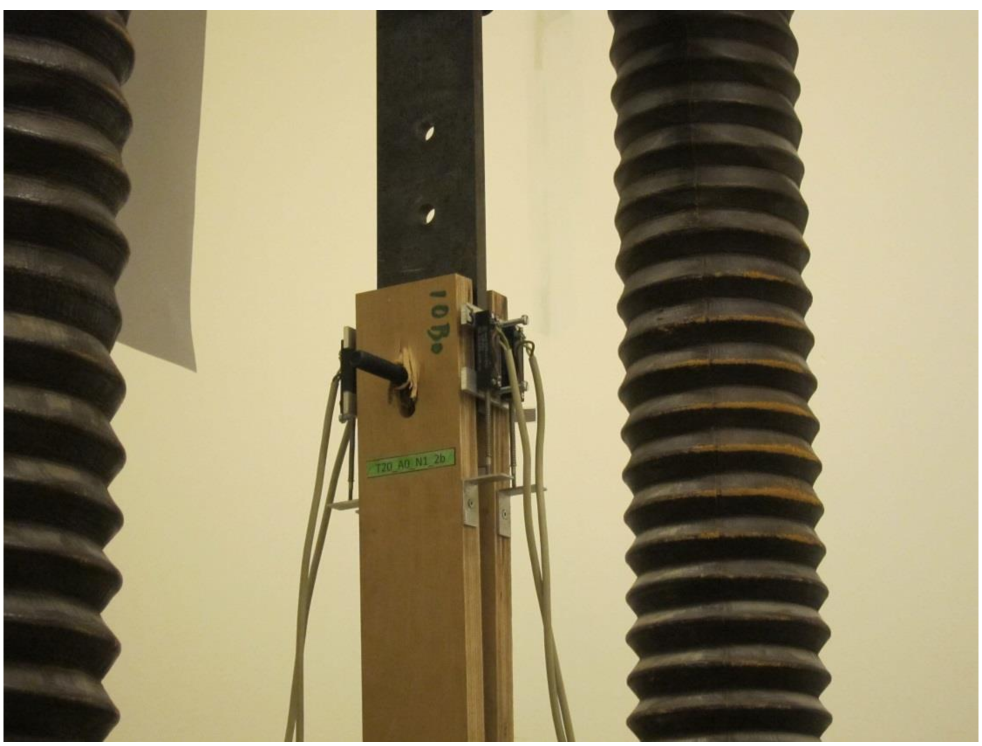


Figure 182 Perspective view nr1. After testing

Data:

T20_A0_N1_2	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	48,40	7,52	1,02	10,10	13,54
$F_{0,5}$	44,70	5,00	0,95	7,47	11,35
$F_{failure}$	-	-	-	-	-

Table 58 Results of specimen T20_A0_N1_2

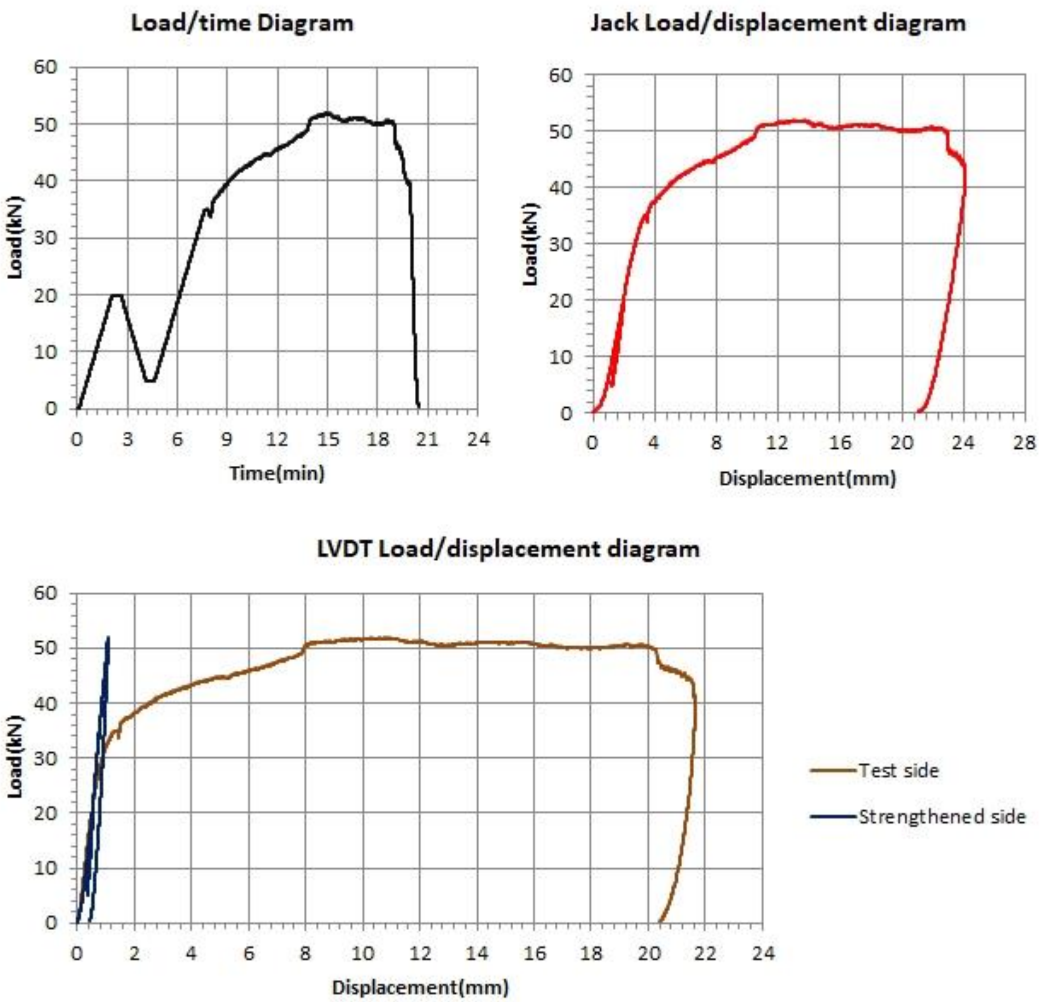


Figure 183 Graphical results of T20_A0_N1_2

13.2.3 T20_A0_N1_3

Material coding:

Labels Timber	T20_A0_N1_3a	T20_A0_N1_3b
Labels Steel Test side	I-140-4	
Labels Steel Strengthened. side	Reused	Reused

Table 59 Material coding T20_A0_N1_3

Log:

Material: *Minor void(not through) located in specimen A, no further important defects*

F_{est}: *50kN*

Displacement controlled speed(1): *0,02mm/s*

Displacement controlled speed(2): *0.04*

During testing: *Photographs were taken during start of the experiment instead of before initiation, so photos could show a little deformation. Additionally the displacement controlled phase was set to 0,2mm per second instead of 0,02 resulting in unusual curves.*

Cause of failure: *embedment failure*

Additional remarks: *Test has been halted around 20mm displacement All specimen are placed with the green label facing outwards, this is not the case for specimen a so do note during photos.*

Figure 184 Perspective view nr1. After testing

Data:

T20_A0_N1_3	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	51,17	9,17	0,96	11,49	8,72
$F_{0,5}$	47,08	5,00	0,88	7,20	8,36
$F_{failure}$	-	-	-	-	-

Table 60 Results of specimen T20_A0_N1_3

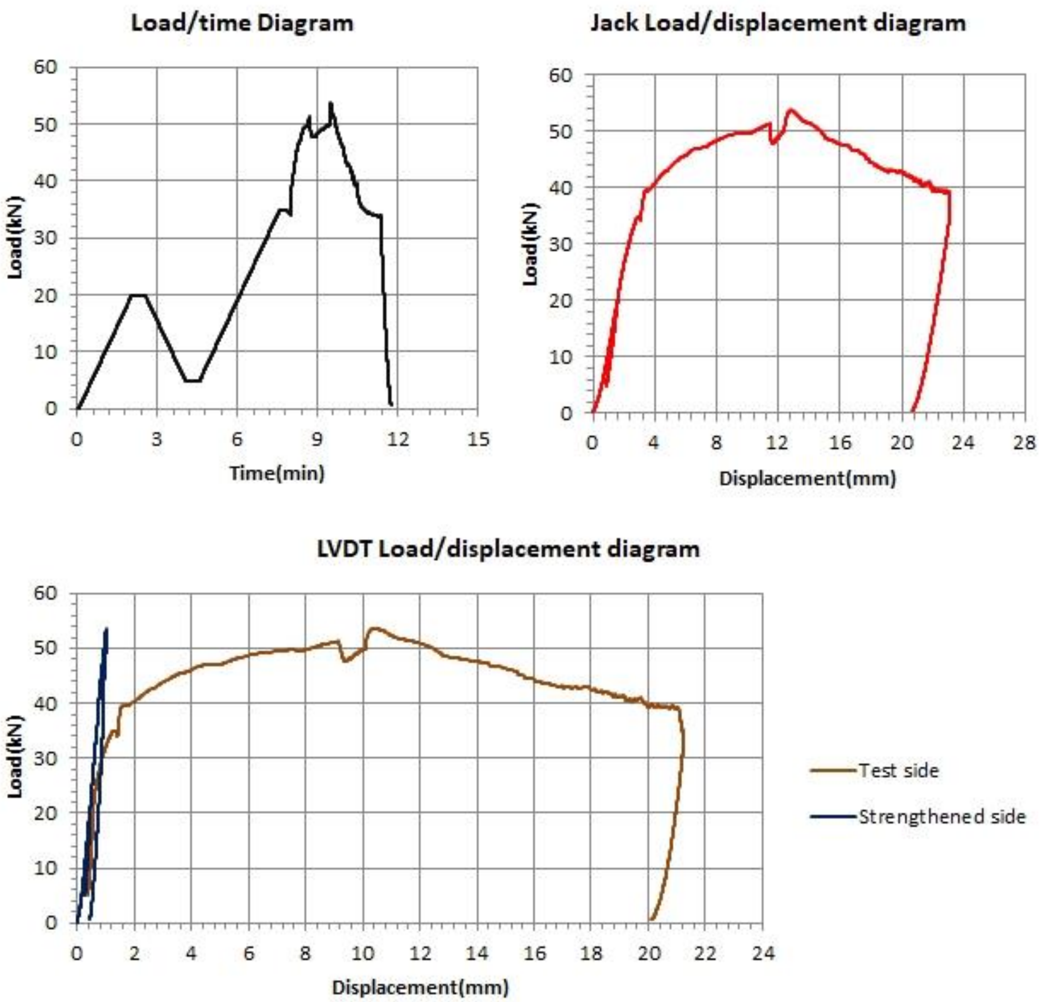


Figure 185 Graphical results of T20_A0_N1_3

13.2.4 T20_A0_N1_4

Material coding:

Labels Timber	T20_A0_N1_4a	T20_A0_N1_4b
Labels Steel Test side	I-140-5	
Labels Steel Strengthened. side	Reused	Reused

Table 61 Material coding T20_A0_N1_4

Log:

Material: *Minor void(not through) located in specimen A, no further important defects*

F_{est}: *50kN*

Displacement controlled speed(1): *0,02mm/s*

Displacement controlled speed(2): *0.04*

During testing: *Small hiccup at 30kN load in which was switched to displacement controlled, which should be at 35kN. Overall procedure went according to guidelines*

Cause of failure: *embedment failure*

Additional remarks: *Test has been halted around 20mm displacement*

Figure 186 Perspective view nr1. After testing

Data:

T20_A0_N1_4	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	50,83	12,00	1,08	14,33	17,10
$F_{0,5}$	48,07	5,00	1,00	7,20	12,07
$F_{failure}$	-	-	-	-	-

Table 62 Results of specimen T20_A0_N1_4

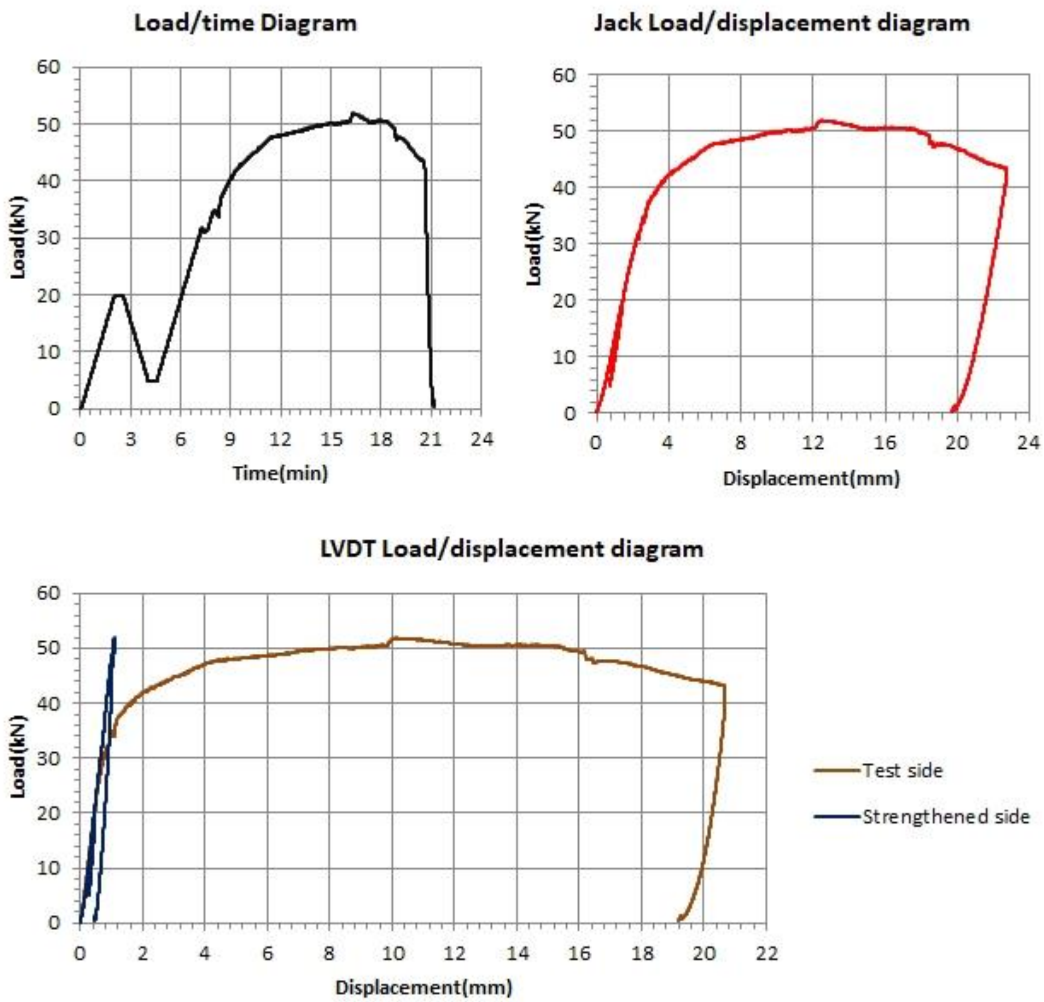


Figure 187 Graphical results of T20_A0_N1_4

13.2.5 T20_A0_N1_5

Material coding:

Labels Timber	T20_A0_N1_5a	T20_A0_N1_5b
Labels Steel Test side	I-140-6	
Labels Steel Strengthened. side	Reused	Reused

Table 63 Material coding T20_A0_N1_5

Log:

Material: *Clear specimen*

F_{est}:*50kN*
Displacement controlled speed(1): *0,02mm/s*
Displacement controlled speed(2): *0.04*

During testing: *Small disruption at 12-13kN in load controlled due to trying something out with the load program. Overall* procedure went according to guidelines.
Cause of failure: *embedment failure*

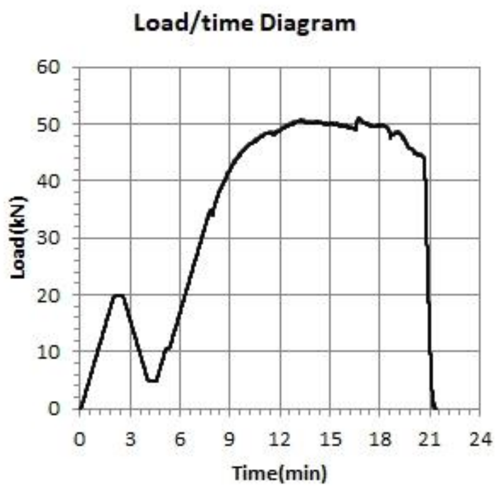
Additional remarks: *Test has been halted around 20mm displacement*

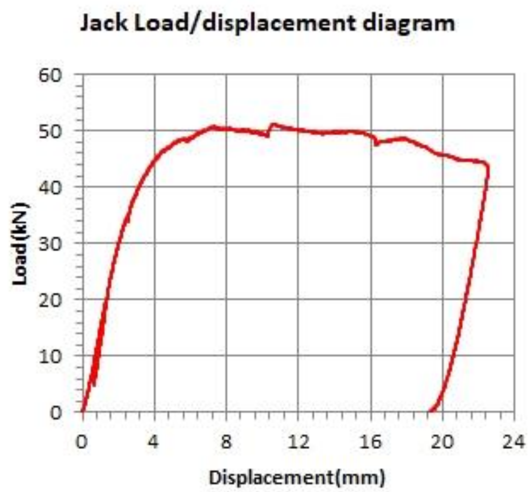
Figure 188 Perspective view nr1. After testing

Data:

T20_A0_N1_5	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	50,70	5,11	1,01	7,33	13,32
$F_{0,5}$	50,61	5,00	1,01	7,22	13,19
$F_{failure}$	-	-	-	-	-

Table 64 Results of specimen T20_A0_N1_5





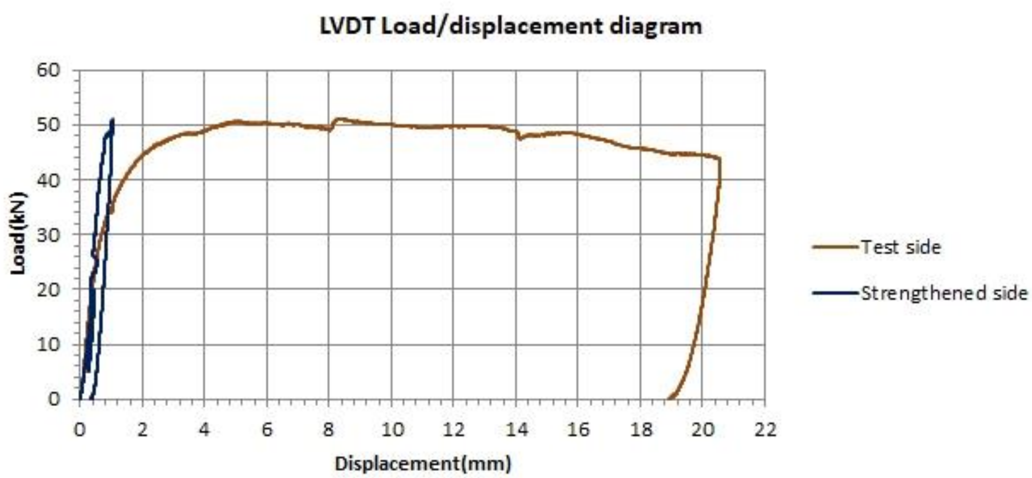


Figure 189 Graphical results of T20_A0_N1_5

13.3 T20_A0_N1_S

<u>Before Testing</u>(pictures test specimen T20_A0_N1_3S shear failure):

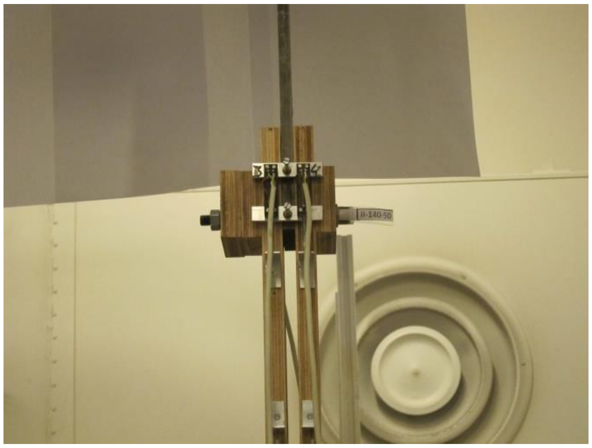


Figure 190 Front view

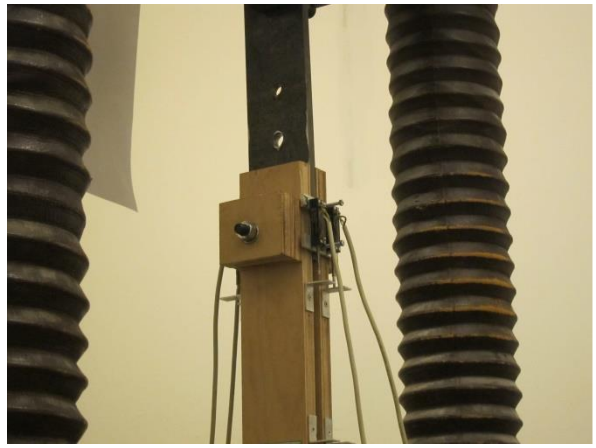


Figure 191 Perspective view nr. 1

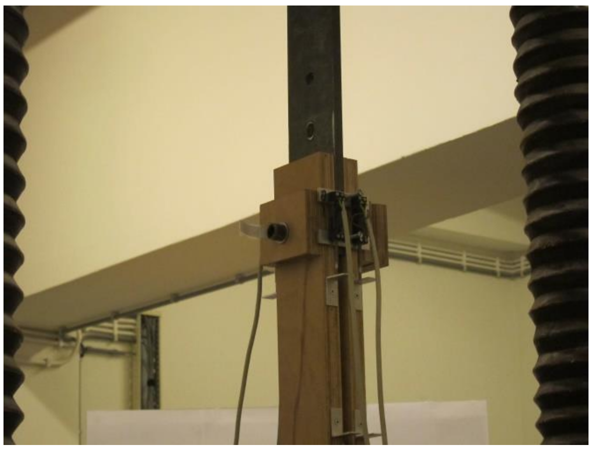


Figure 192 Perspective view nr 2

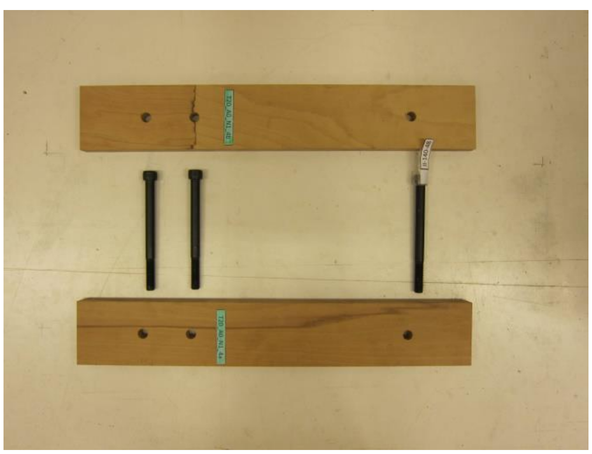


Figure 193 Overview materials

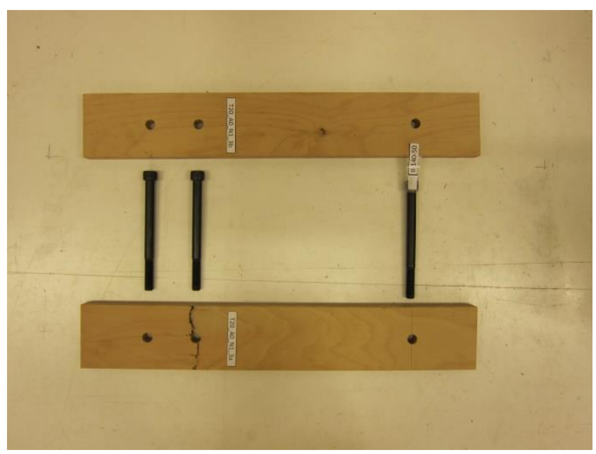


Figure 194 Overview materials

<u>After testing</u>

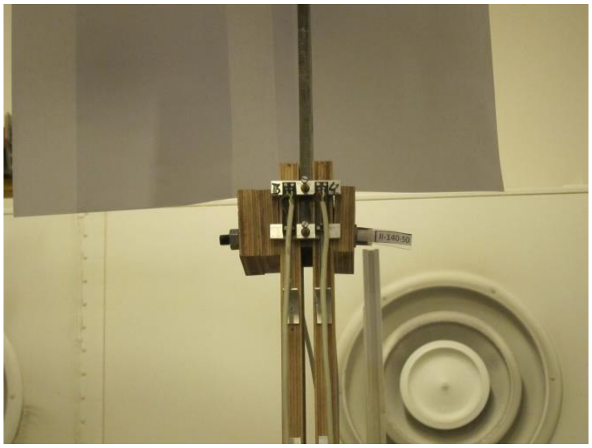


Figure 195 Front view

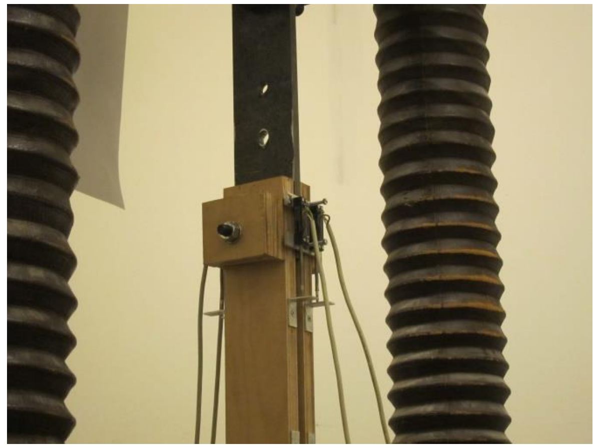


Figure 196 Perspective view nr. 1

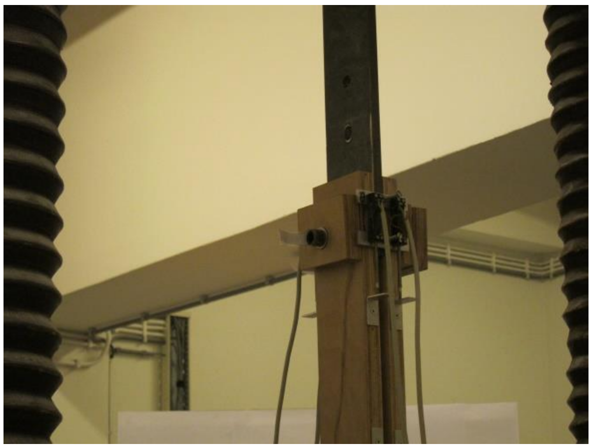


Figure 197 Perspective view nr 2

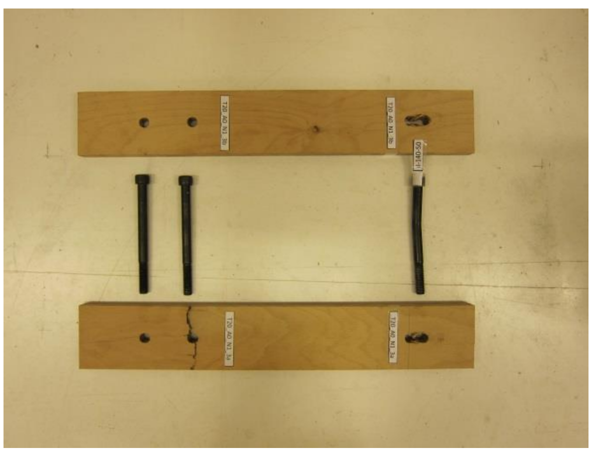


Figure 198 Overview materials

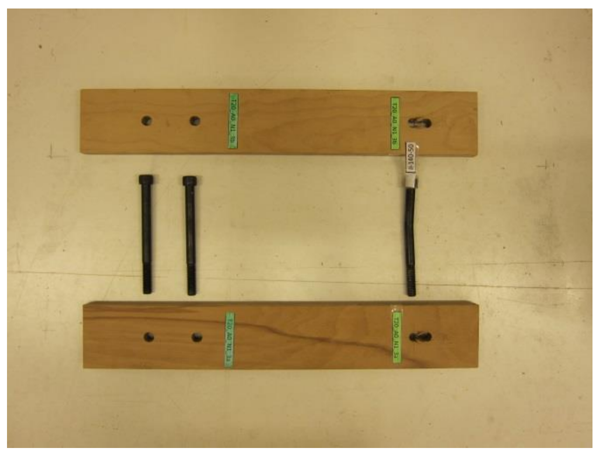


Figure 199 Overview materials

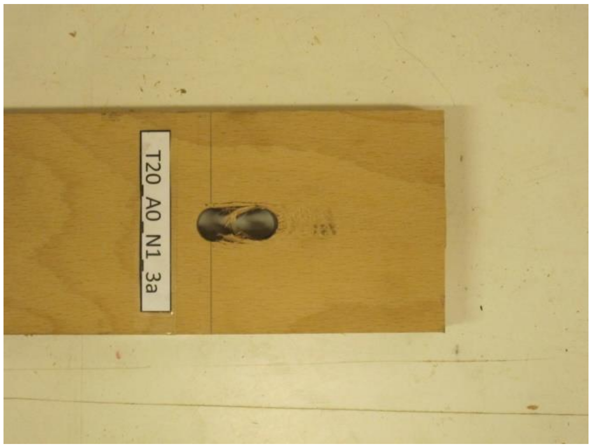


Figure 200 Closeup failure(Surface towards steel plate))

Figure 202 Closeup failure(Surface on the outside)

Figure 201 Closeup failure(Surface towards steel plate))

Figure 203 Figure 204 Closeup failure(Surface on the outside)

Figure 205 Dowels after testing strengthened side

Figure 206 Dowels after testing test side

13.3.1 T20_A0_N1_3S

Material coding:

Labels Timber	T20_A0_N1_3a	T20_A0_N1_3a
Labels Steel Test side	II-140-50	
Labels Steel Strengthened. side	new	new

Table 65 Material coding T20_A0_N1_3S

Log:

Material: *Clear specimen*
F_{est}: *65kN*
Displacement controlled speed(1): *0.04mm/s*
Displacement controlled speed(2): *-mm/s*

During testing: *as planned*
Cause of failure: *Shear failure*

Additional remarks: *holes strengthened side has been used in test T20_A0_N1_3*

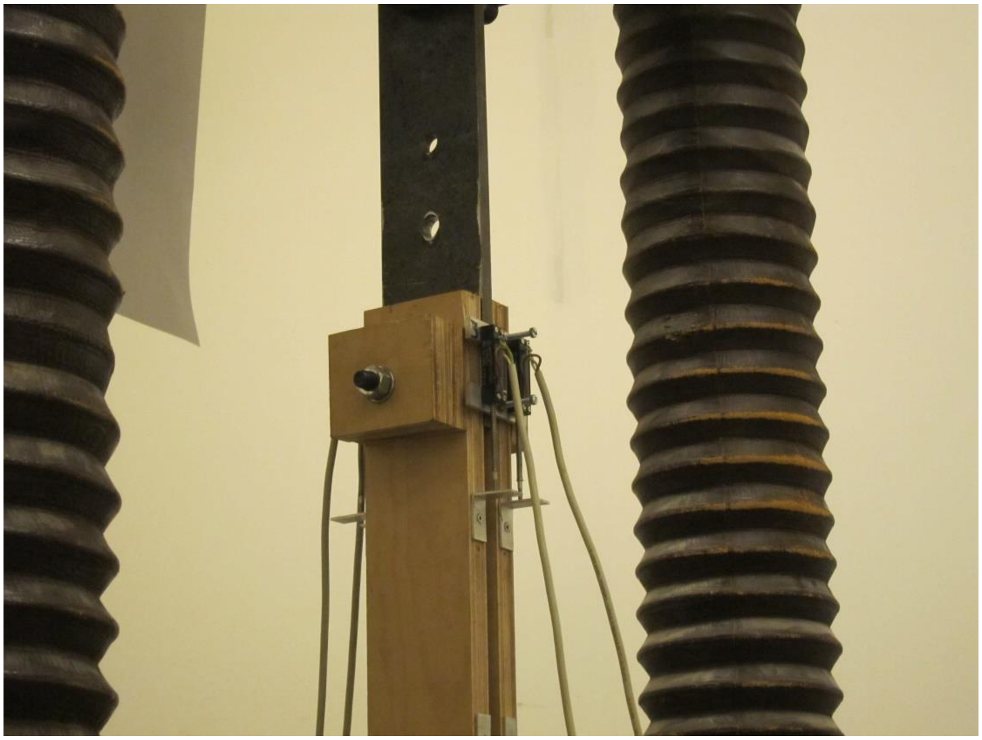


Figure 207 Perspective view nr1. After testing

Data:

T20_A0_N1_3S	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	64.66	14.05	2.36	18.75	12.68
$F_{0,5}$	50.88	5.00	2.01	9.00	8.61
$F_{failure}$	68.19	20.50	2.64	25.44	15.47

Table 66 Results of specimen T20_A0_N1_3S

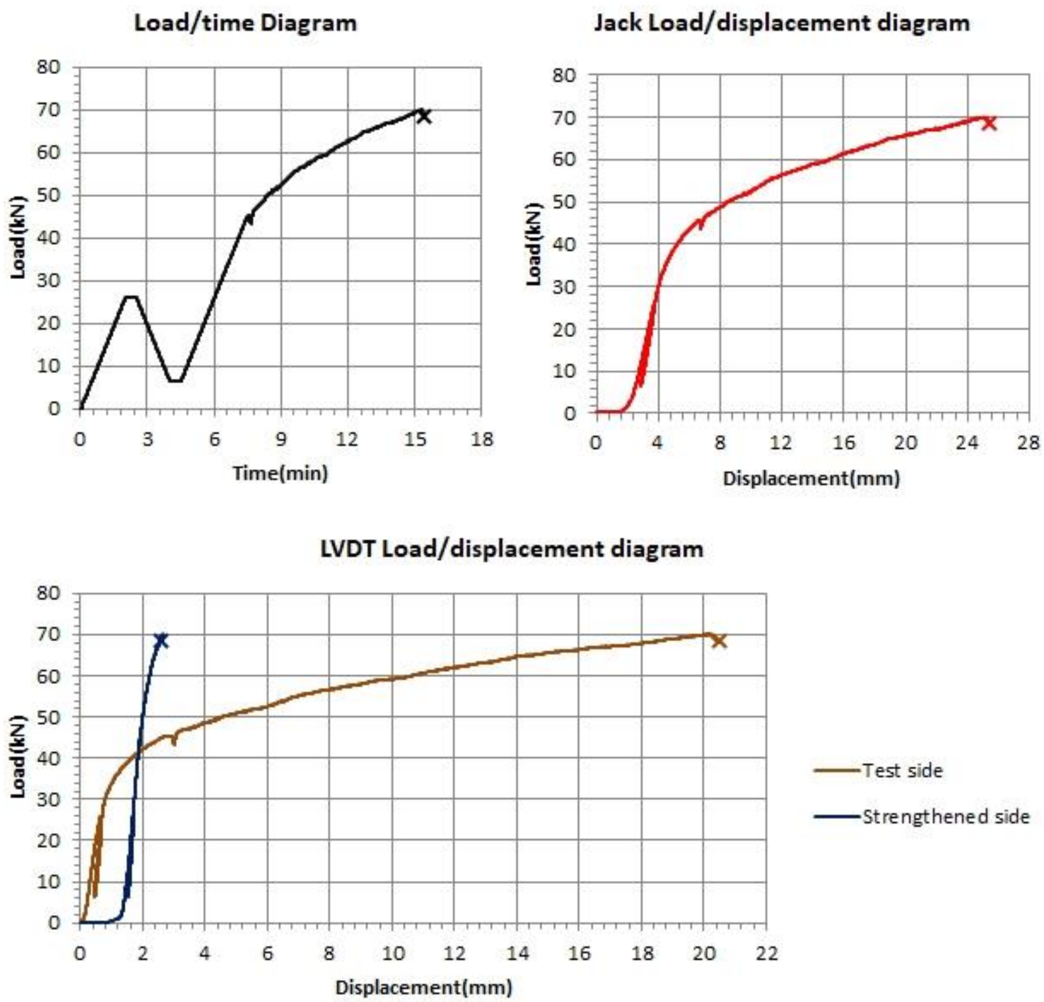


Figure 208 Graphical results of T20_A0_N1_3S

13.3.2 T20_A0_N1_4S

Material coding:

Labels Timber	T20_A0_N1_4a	T20_A0_N1_4a
Labels Steel Test side	II-140-48	
Labels Steel Strengthened. side	new	new

Table 67 Material coding T20_A0_N1_4S

Log:

Material: *clear specimen*
F_{est}: *60kN*
Displacement controlled speed(1): *0.03mm/s*
Displacement controlled speed(2): *-mm/s*

During testing: *as planned*
Cause of failure: *Shear failure*

Additional remarks: *holes strengthened side has been used in test T20_A0_N1_4*

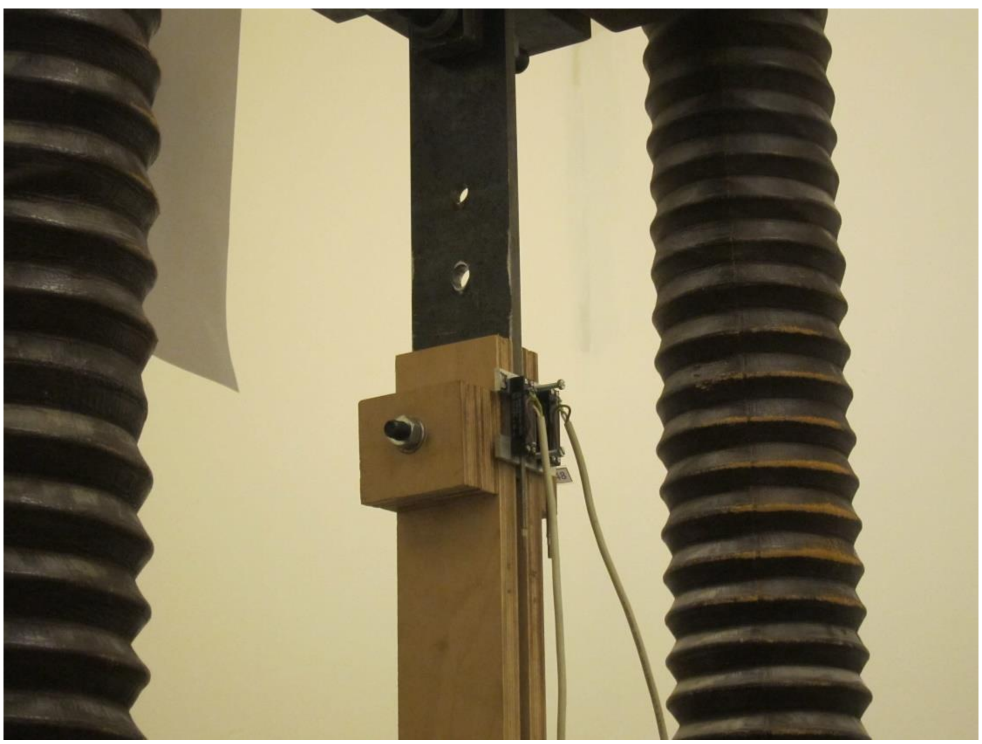


Figure 209 Perspective view nr1. After testing

Data:

T20_A0_N1_4S	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	61.52	11.96	1.90	15.98	13.73
$F_{0,5}$	50.45	5.00	1.69	8.49	9.57
$F_{failure}$	61.86	17.29	2.03	21.40	16.78

Table 68 Results of specimen T20_A0_N1_4S

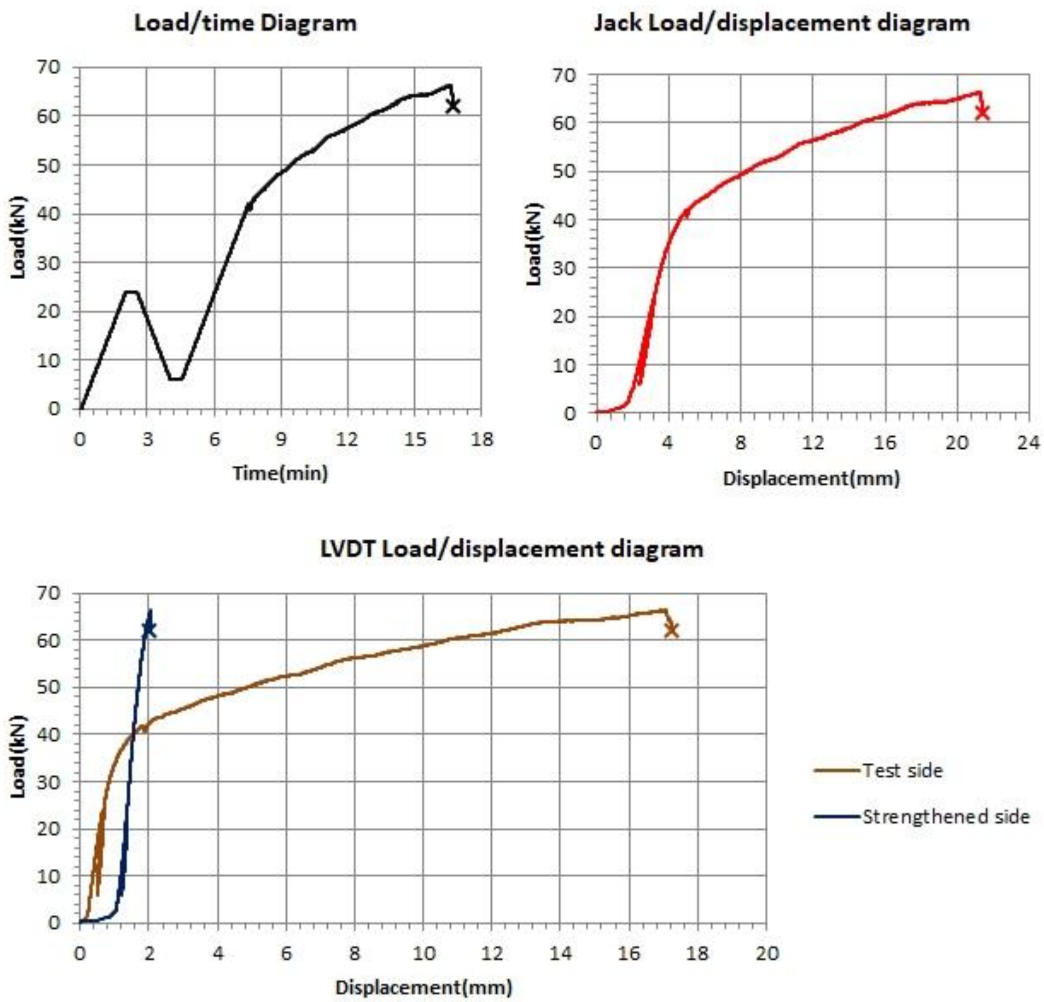


Figure 210 Graphical results of T20_A0_N1_4S

13.3.3 T20_A0_N1_5S

Material coding:

Labels Timber	T20_A0_N1_5a	T20_A0_N1_5a
Labels Steel Test side	II-140-49	
Labels Steel Strengthened. side	new	new

Table 69 Material coding T20_A0_N1_5S

Log:

Material: *clear specimen*
F_{est}: *65kN*
Displacement controlled speed(1): *0.035mm/s*
Displacement controlled speed(2): *-mm/s*

During testing: *as planned*
Cause of failure: *Shear failure*

Additional remarks: *holes strengthened side has been used in test T20_A0_N1_5*

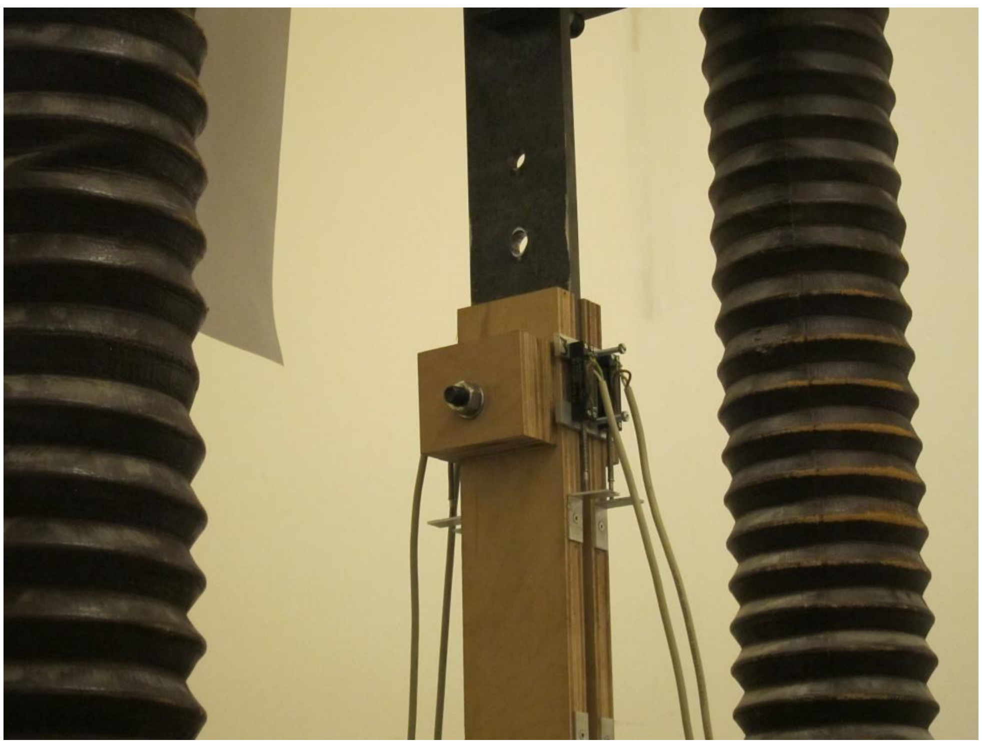
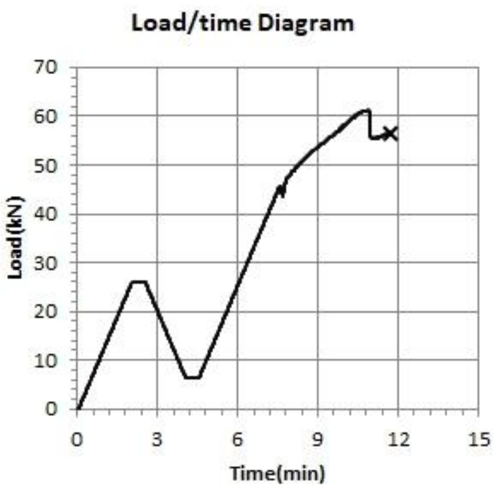


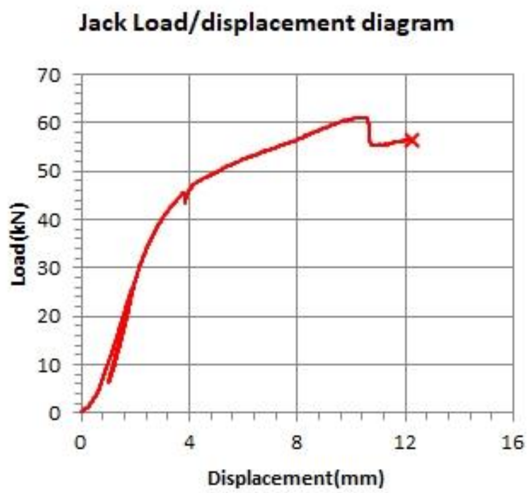
Figure 211 Perspective view nr1. After testing

Data:

T20_A0_N1_5S	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	61.23	7.77	1.00	10.51	10.88
$F_{0,5}$	55.59	5.00	0.87	7.48	9.43
$F_{failure}$	56.26	9.61	1.02	12.27	11.72

Table 70 Results of specimen T20_A0_N1_5S





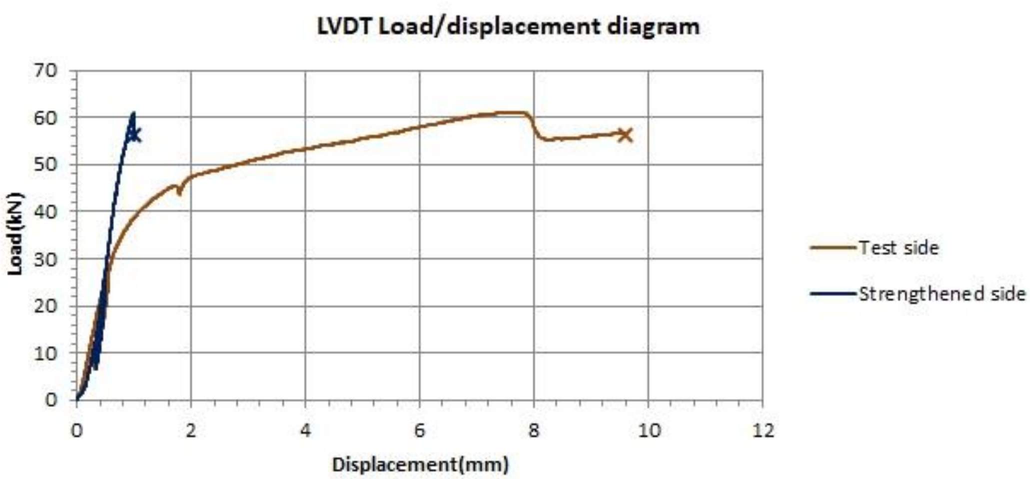


Figure 212 Graphical results of T20_A0_N1_5S

13.4 T20_A0_N1R

<u>Before Testing</u>(pictures test specimen T20_A0_N1R_1 shear failure):

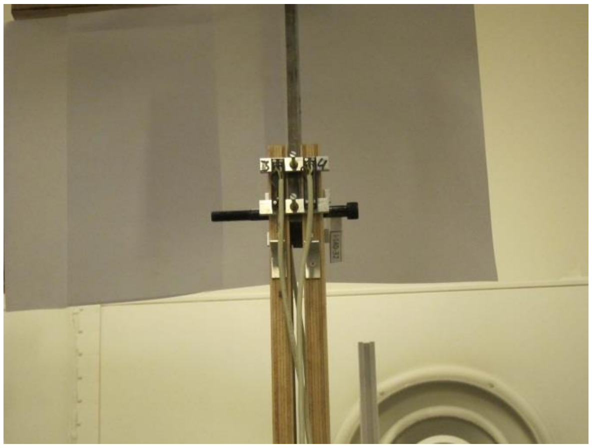


Figure 213 Front view

Figure 214 Perspective view nr. 1

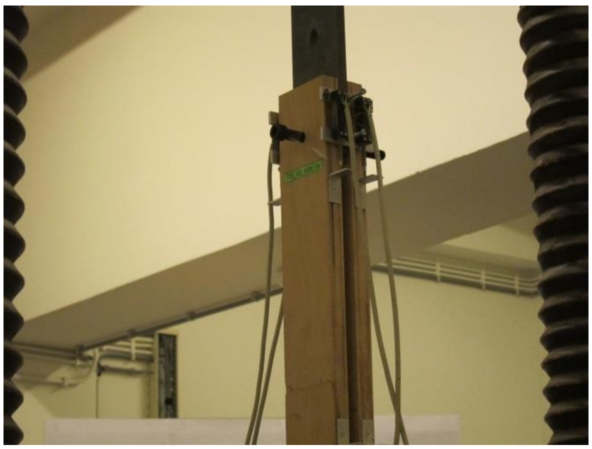


Figure 215 Perspective view nr 2

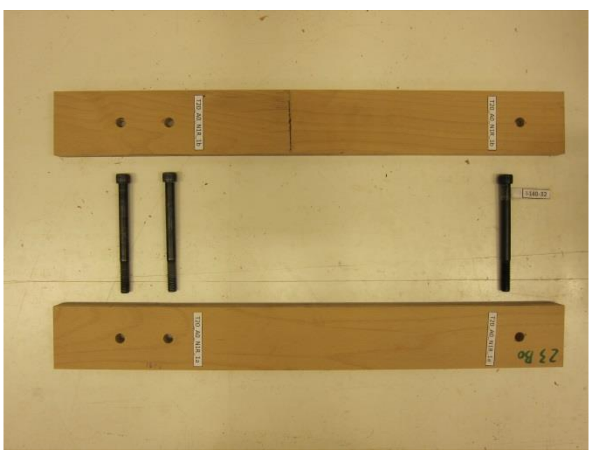


Figure 216 Overview materials

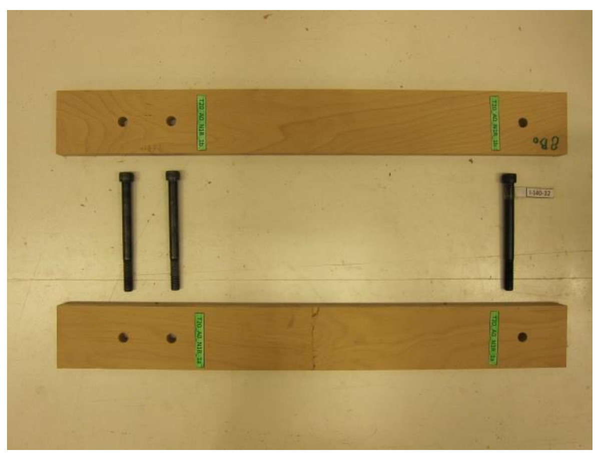


Figure 217 Overview materials

<u>After testing</u>

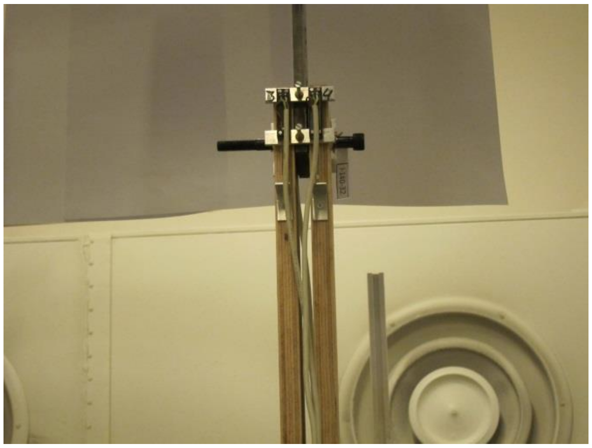


Figure 218 Front view


Figure 219 Perspective view nr. 1

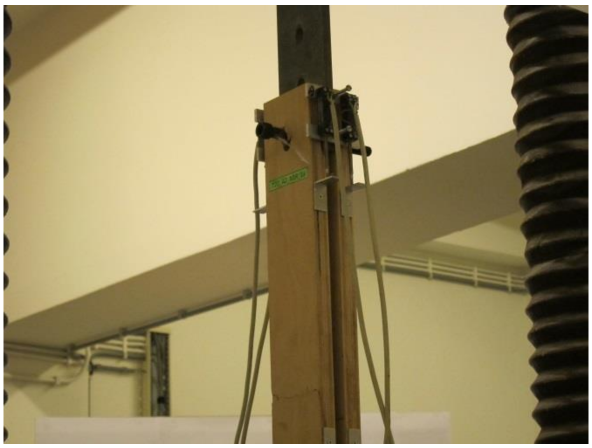


Figure 220 perspective view nr 2


Figure 221 closeup of shear failure top position

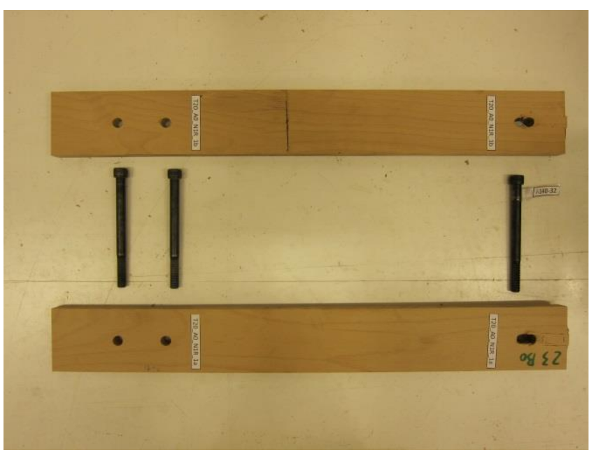


Figure 222 Overview materials

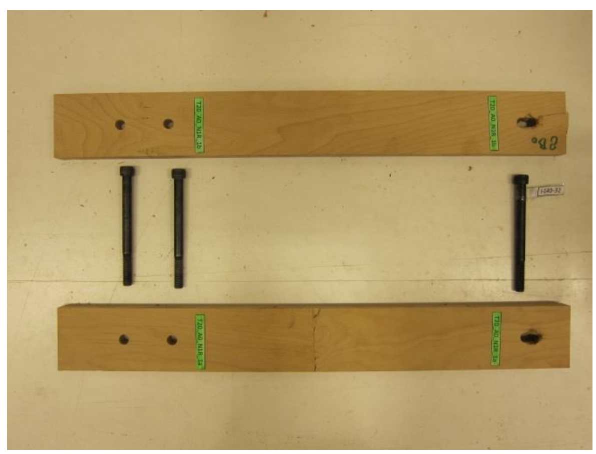


Figure 223 Overview materials

Figure 224 Closeup failure(Surface towards steel plate)

Figure 225 Closeup failure(Surface towards steel plate)

Figure 226 Closeup failure(Surface on the outside)

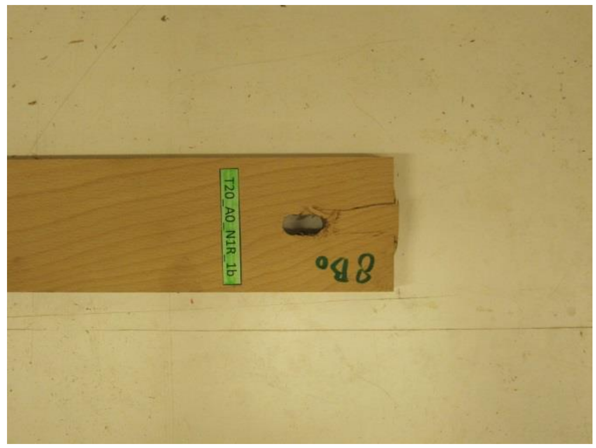


Figure 227 Closeup failure(Surface on the outside)

Figure 228 Dowels after testing strengthened side

Figure 229 dowels after testing test side

13.4.1 T20_A0_N1R_1

Material coding:

Labels Timber	T20_A0_N1R_1a	T20_A0_N1R_1b
Labels Steel Test side	I-140-32	
Labels Steel Strengthened. side	Reused	Reused

Table 71 Material coding T20_A0_N1R_1

Log:

Material: Clear specimen

F_{est}: *50kN*
Displacement controlled speed(1): *0.018mm/s*
Displacement controlled speed(2): *-mm/s*

During testing: *as planned*

Cause of failure: *(block)shear failure*

Additional remarks:

Figure 230 Perspective view nr1. After testing

Data:

T20_A0_N1R_1	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	49,26	7,57	1,09	10,27	14,60
$F_{0,5}$	47,19	4,99	1,02	7,55	12,08
$F_{failure}$	41,45	12,44	1,11	15,00	18,98

Table 72 Results of specimen T20_A0_N1R_1

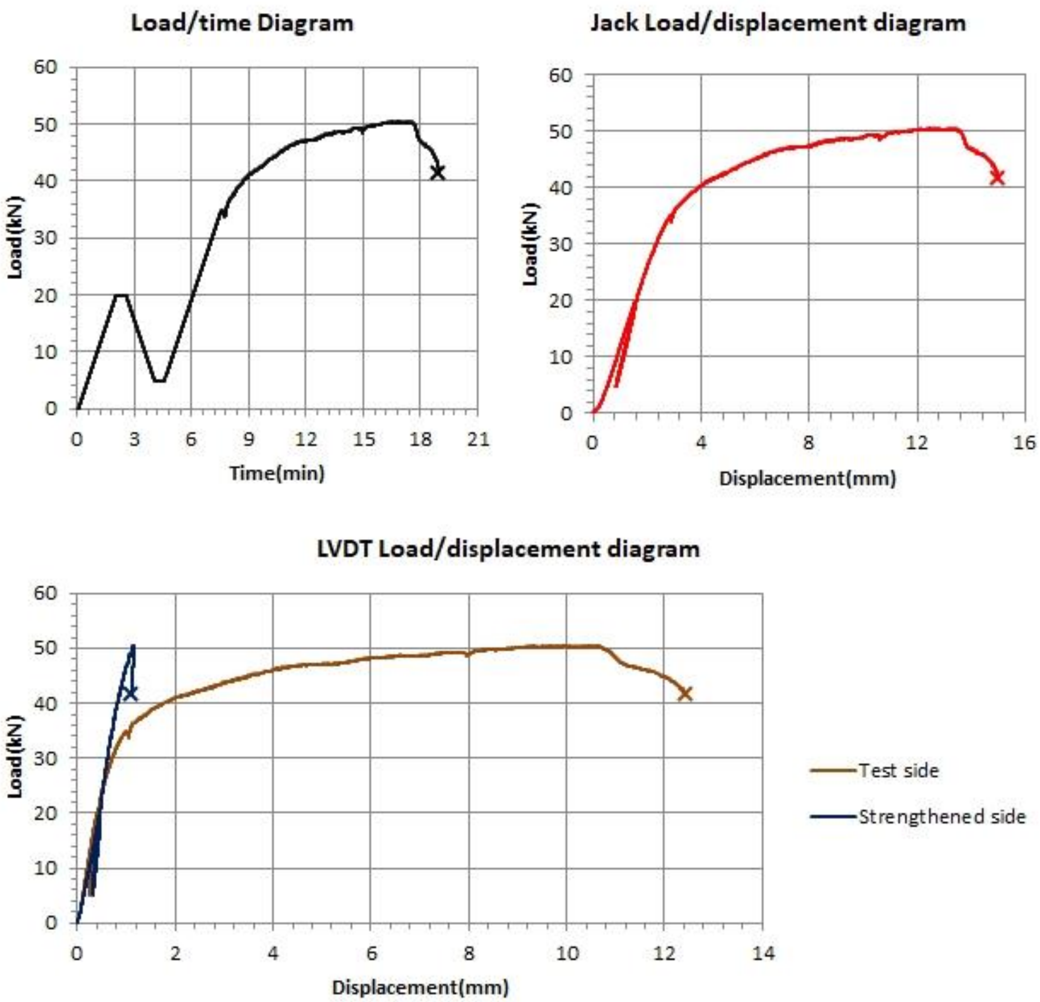


Figure 231 Graphical results of T20_A0_N1R_1

13.4.2 T20_A0_N1R_2

Material coding:

Labels Timber	T20_A0_N1R_2a	T20_A0_N1R_2b
Labels Steel Test side	I-140-33	
Labels Steel Strengthened. side	Reused	Reused

Table 73 Material coding T20_A0_N1R_2

Log:

Material: *Clear specimen*

F_{est}: *50kN*
Displacement controlled speed(1): *0.02mm/s*
Displacement controlled speed(2): *-mm/s*

During testing: *test was halted after veneer sheared off to observe the failure mechanism*

Cause of failure: *Block shear specimen b*

Additional remarks:

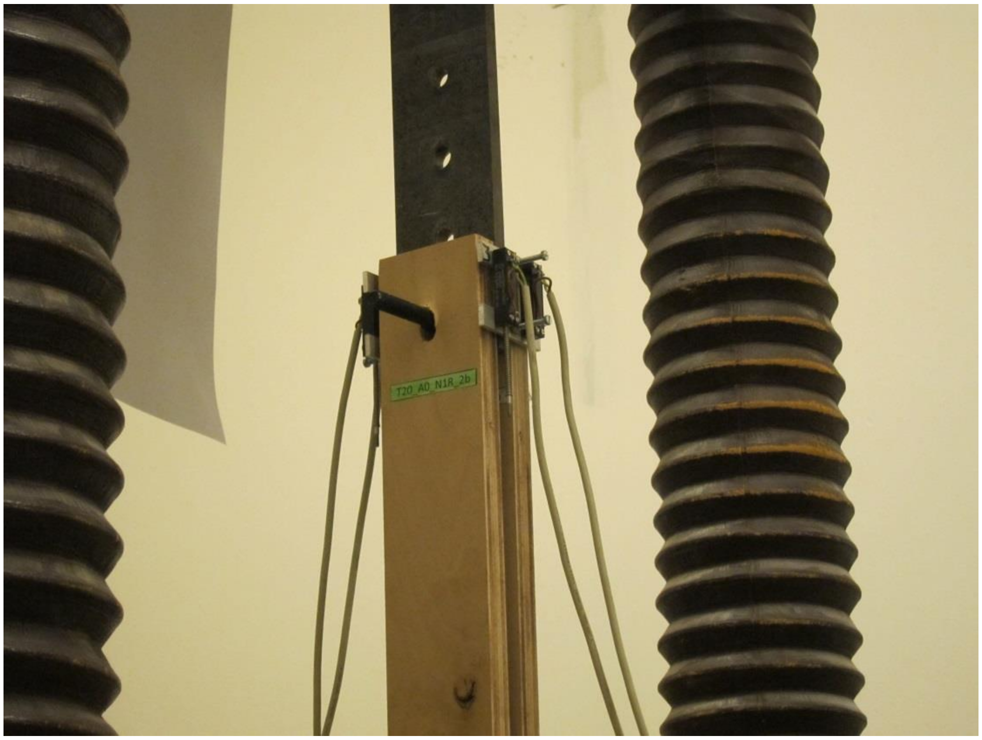


Figure 232 Perspective view nr1. After testing

Data:

T20_A0_N1R_2	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	46,86	9,05	0,90	11,43	14,90
$F_{0,5}$	44,49	5,00	0,85	7,20	11,37
$F_{failure}$	35,82	11,80	0,81	13,82	16,92

Table 74 Results of specimen T20_A0_N1R_2

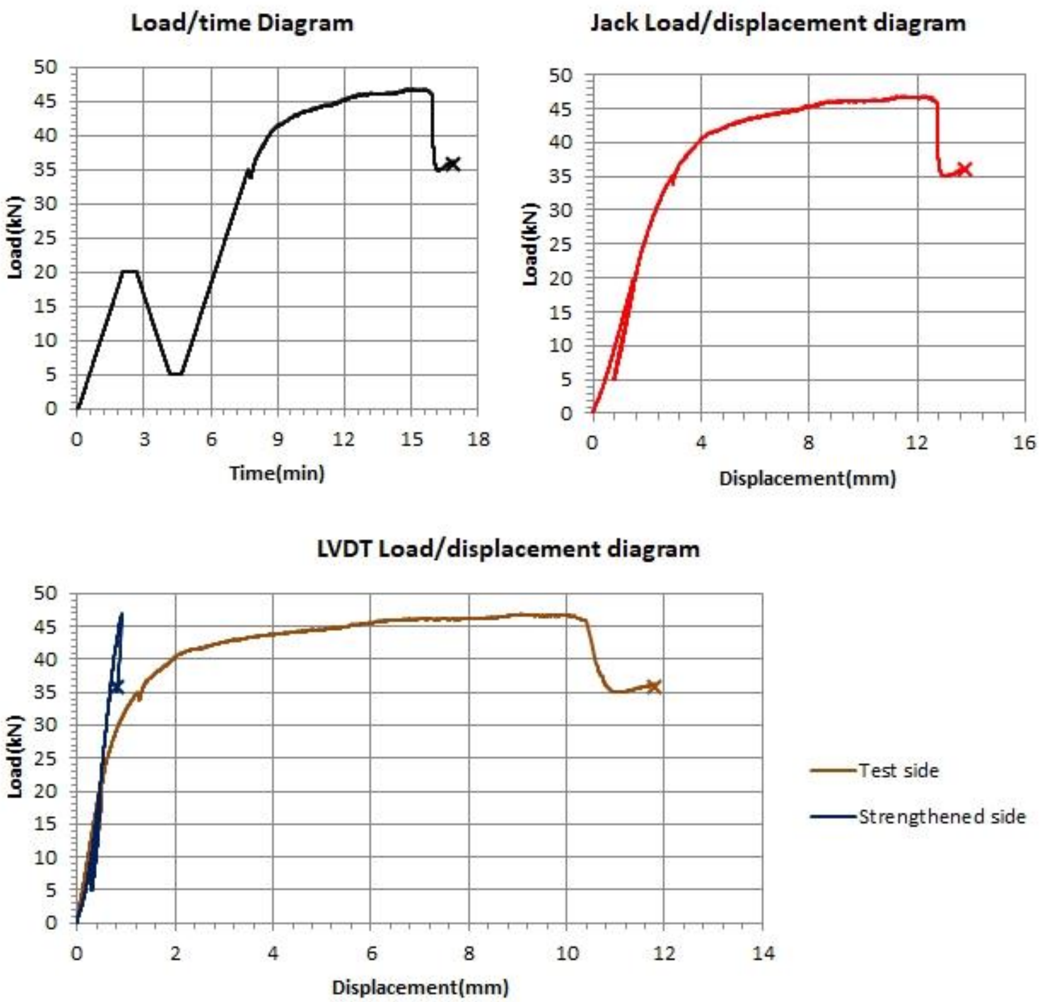


Figure 233 Graphical results of T20_A0_N1R_2

13.4.3 T20_A0_N1R_3

Material coding:

Labels Timber	T20_A0_N1R_3a	T20_A0_N1R_3b
Labels Steel Test side	I-140-34	
Labels Steel Strengthened. side	Reused	Reused

Table 75 Material coding T20_A0_N1R_3

Log:

Material: *Specimen a clear specimen, specimen b contains multiple tiny voids of less than 5mm*

F_{est}: *50kN*

Displacement controlled speed(1): *0.02mm/s*
Displacement controlled speed(2): *-mm/s*

During testing: *Test was halted after a a small veneer sheared. This was also at a displacement 15mm which is the boundary for testing*

Cause of failure: *Shear failure(however not fully developed)*

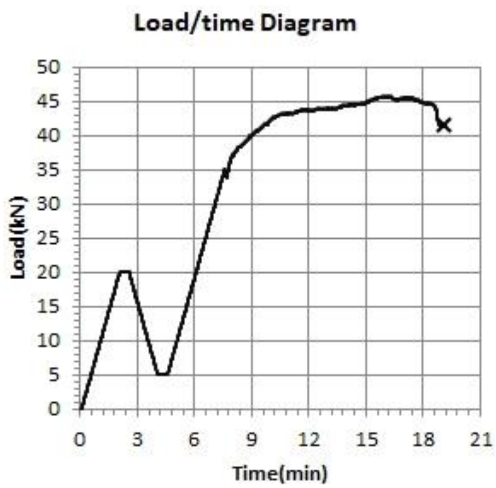
Additional remarks:

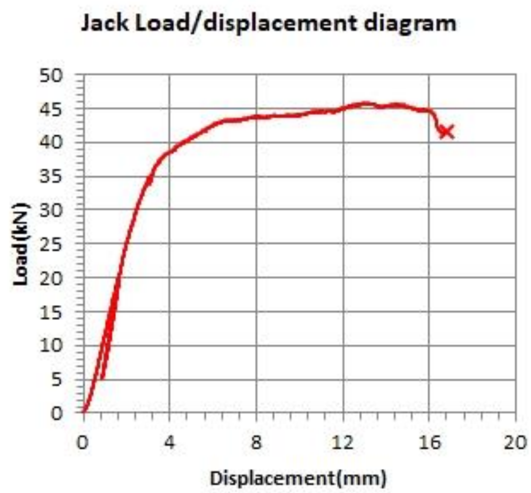
Figure 234 Perspective view nr1. After testing

Data:

T20_A0_N1R_3	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	45,82	11,04	0,94	13,17	16,10
$F_{0,5}$	43,43	5,00	0,88	7,10	11,03
$F_{failure}$	41,42	14,81	0,93	16,83	19,15

Table 76 Results of specimen T20_A0_N1R_3





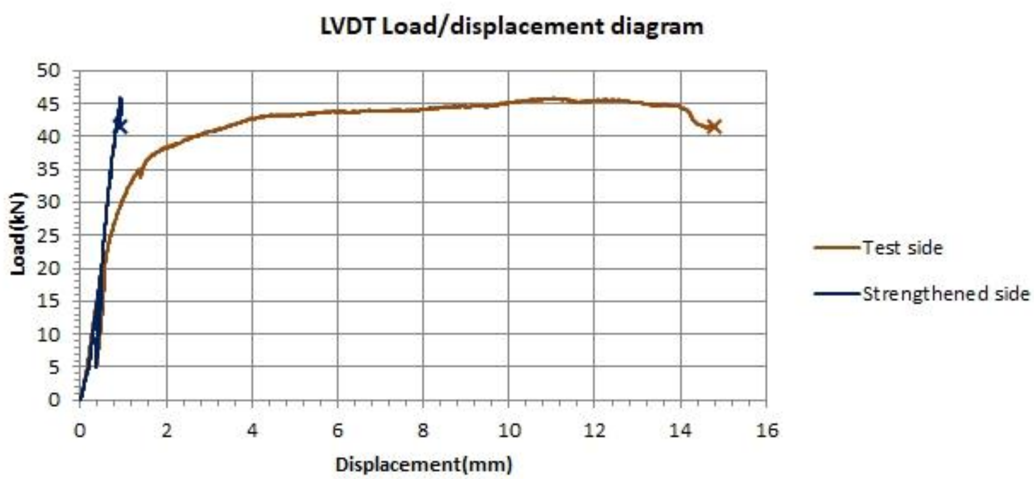


Figure 235 Graphical results of T20_A0_N1R_3

13.4.4 T20_A0_N1R_4

Material coding:

Labels Timber	T20_A0_N1R_4a	T20_A0_N1R_4b
Labels Steel Test side	I-140-35	
Labels Steel Strengthened. side	Reused	Reused

Table 77 Material coding T20_A0_N1R_4

Log:

Material: *Small voids in specimen a. Specimen b clear specimen.*
F_{est}: *50kN*
Displacement controlled speed(1): *0.02mm/s*
Displacement controlled speed(2): *mm/s*

During testing: *as planned*

Cause of failure: *Shear failure*

Additional remarks:

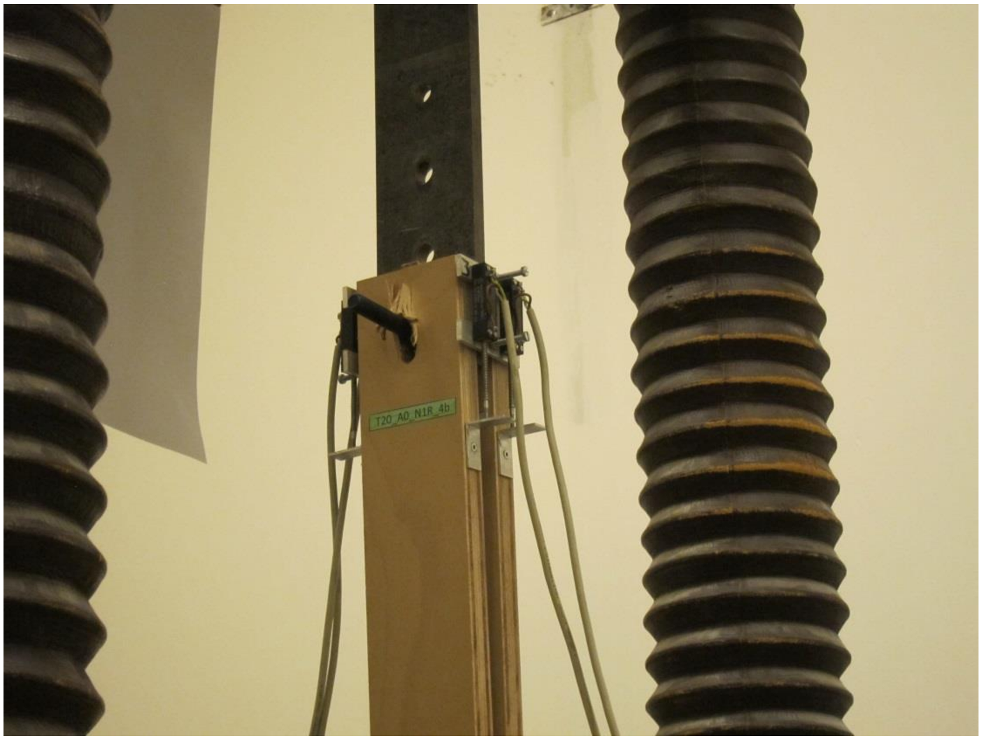


Figure 236 Perspective view nr1. After testing

Data:

T20_A0_N1R_4	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	48,87	7,36	0,86	9,88	13,69
$F_{0,5}$	47,60	5,00	0,82	7,46	11,67
$F_{failure}$	37,38	13,53	0,80	15,69	18,53

Table 78 Results of specimen c T20_A0_N1R_4

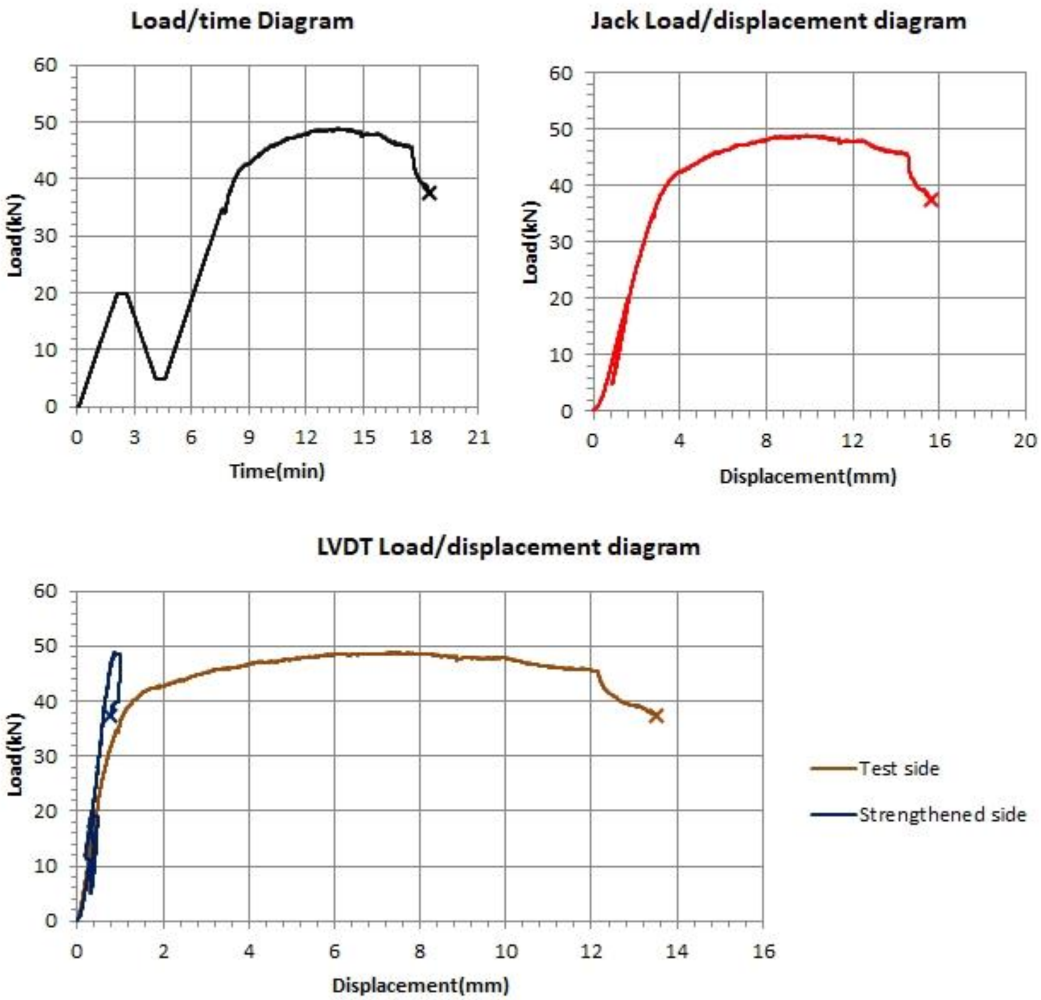


Figure 237 Graphical results of T20_A0_N1R_4

13.4.5 T20_A0_N1R_5

Material coding:

Labels Timber	T20_A0_N1R_5a	T20_A0_N1R_5b
Labels Steel Test side	I-140-36	
Labels Steel Strengthened. side	Reused	Reused

Table 79 Material coding T20_A0_N1R_5

Log:

Material: *Clear specimen*

F_{est}: *50kN*
Displacement controlled speed(1): *0.02mm/s*
Displacement controlled speed(2): *-mm/s*

During testing: *as planned*

Cause of failure: *shear failure*

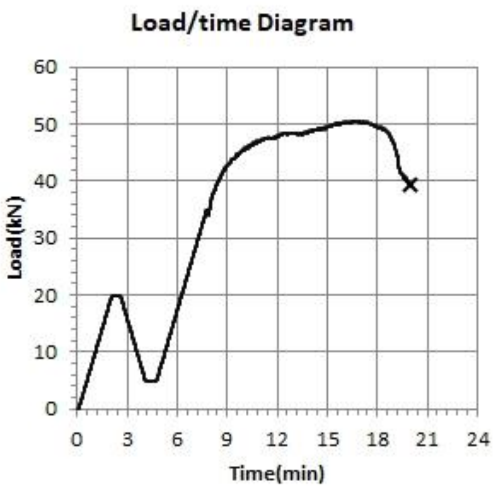
Additional remarks: *both specimen showed micro cracks before dropping in capacity*

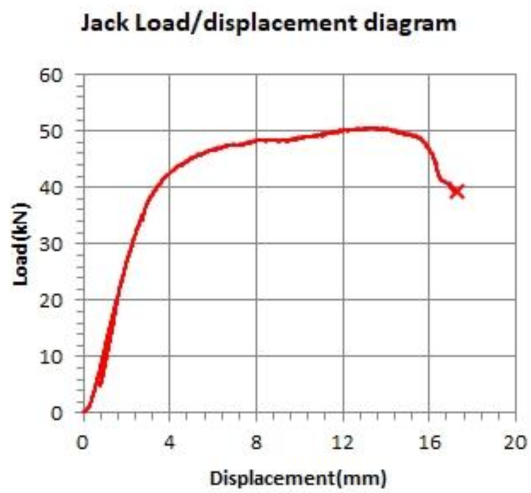
Figure 238 Perspective view nr1. After testing

Data:

T20_A0_N1R_5	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	50,63	10,67	0,93	13,20	16,63
$F_{0,5}$	47,64	4,99	0,87	7,46	11,85
$F_{failure}$	39,31	15,03	0,87	17,28	20,03

Table 80 Results of specimen T20_A0_N1R_5





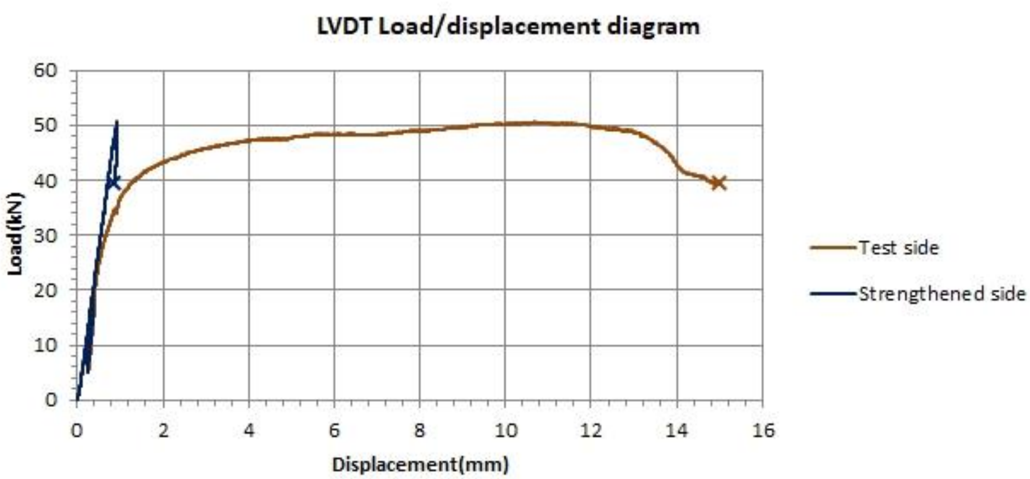


Figure 239 Graphical results of T20_A0_N1R_5

13.5 T20_A0_N1R_S

Before Testing**(pictures test specimen T20_A0_N1R_1S shear failure)**:

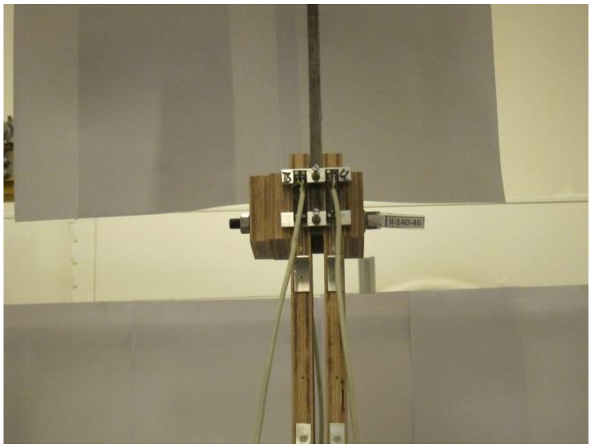


Figure 240 Front view

Figure 241 Perspective view nr. 1

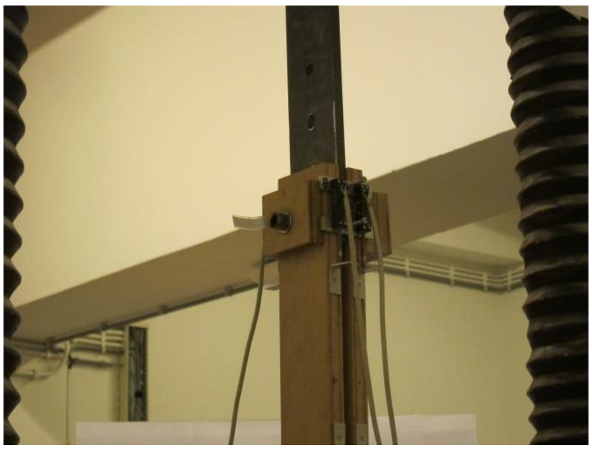


Figure 242 Perspective view nr 2

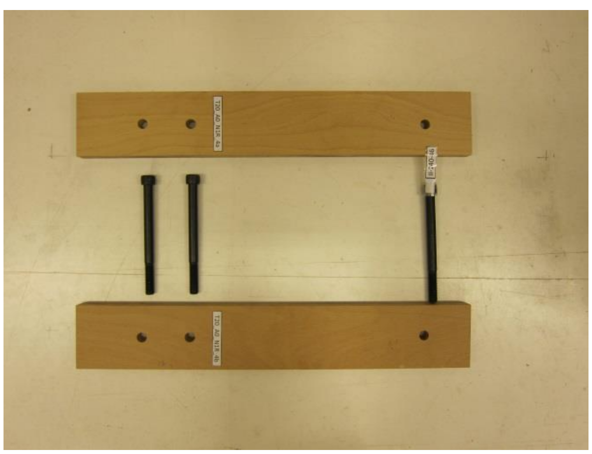


Figure 243 Overview materials

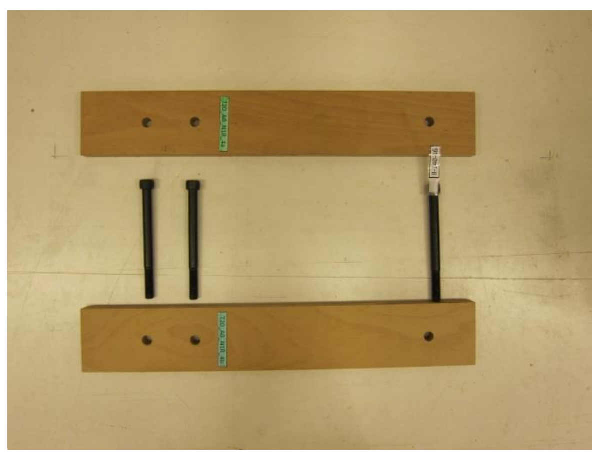


Figure 244 Overview materials

After testing

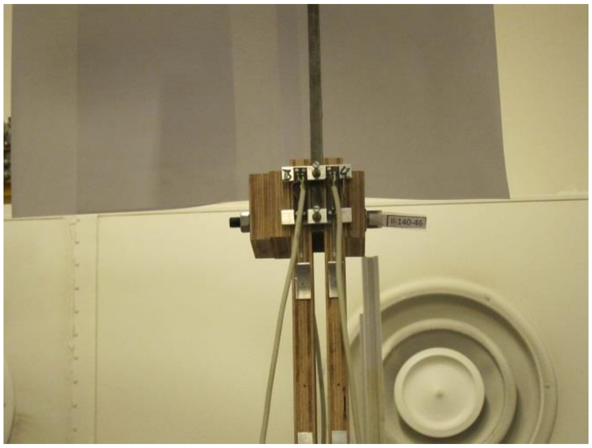


Figure 245 Front view

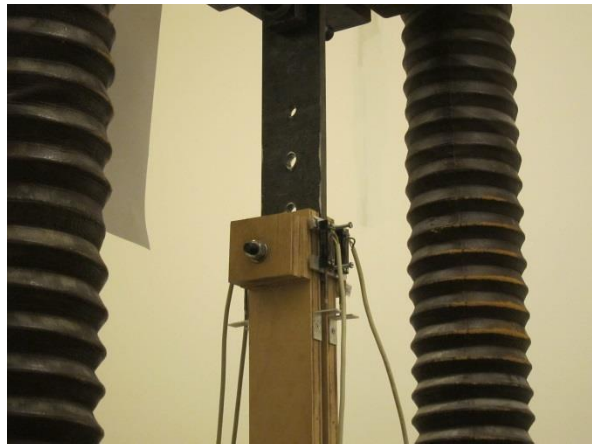


Figure 246 Perspective view nr. 1

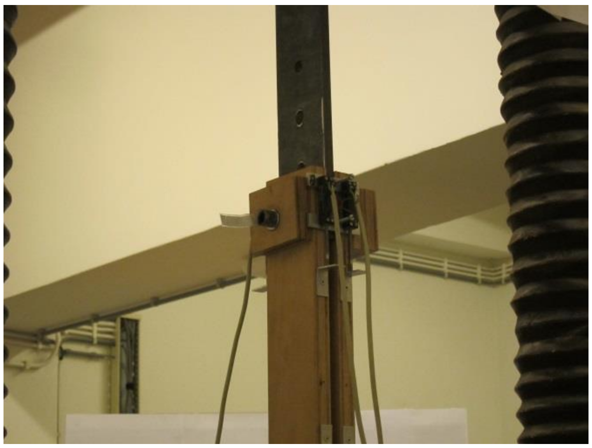


Figure 247 perspective view nr 2

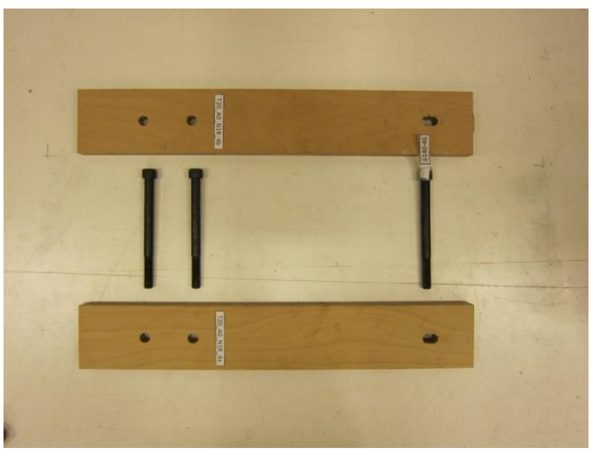


Figure 248 Overview materials

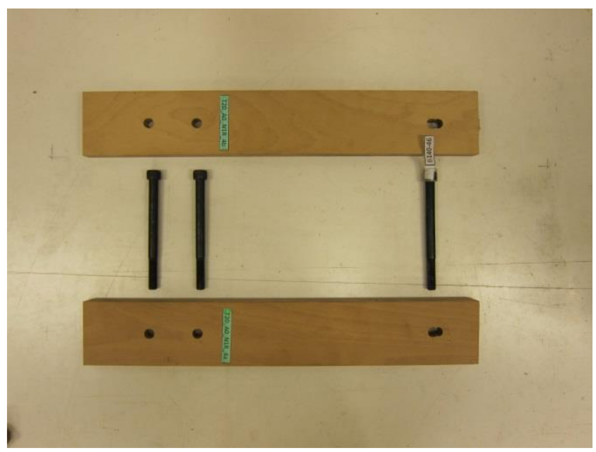


Figure 249 Overview materials

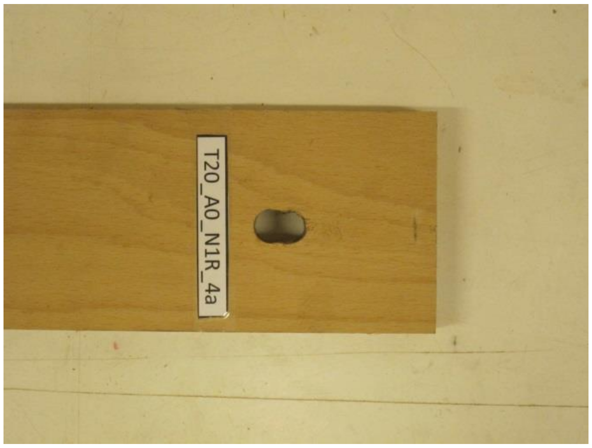


Figure 250 Closeup failure(Surface towards steel plate)

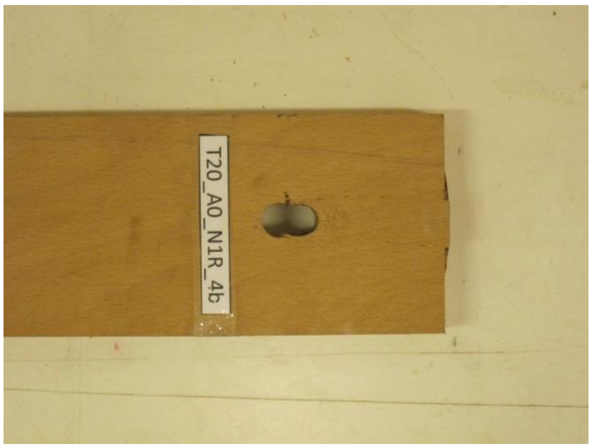


Figure 251 Closeup failure(Surface towards steel plate)

Figure 252 Closeup failure(Surface on the outside)

Figure 253 Closeup failure(Surface on the outside)

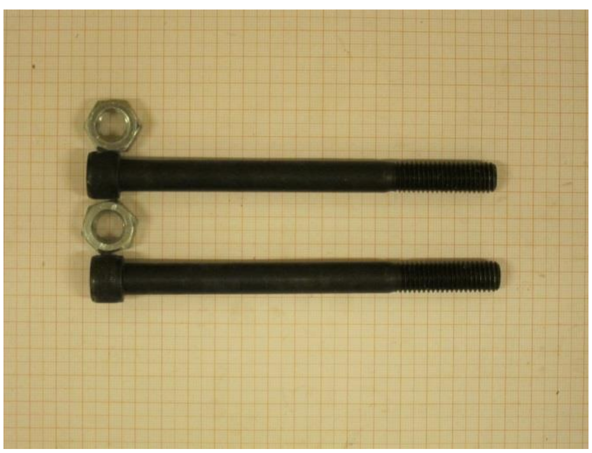


Figure 254 Dowels after testing strengthened side

Figure 255 dowels after testing test side

13.5.1 T20_A0_N1R_3S

Material coding:

Labels Timber	T20_A0_N1R_3Sa	T20_A0_N1R_3Sb
Labels Steel Test side	II-140-51	
Labels Steel Strengthened. side	New(set II)	New(set II)

Table 81 Material coding T20_A0_N1R_3S

Log:

Material: *reused specimen, see previous test for condition*
F_{est}: *60kN*
Displacement controlled speed(1): *0.04mm/s*
Displacement controlled speed(2): *mm/s*

During testing: *as planned*

Cause of failure: *shear failure*

Additional remarks: *significantly lower capacity due to shearing of some veneers*

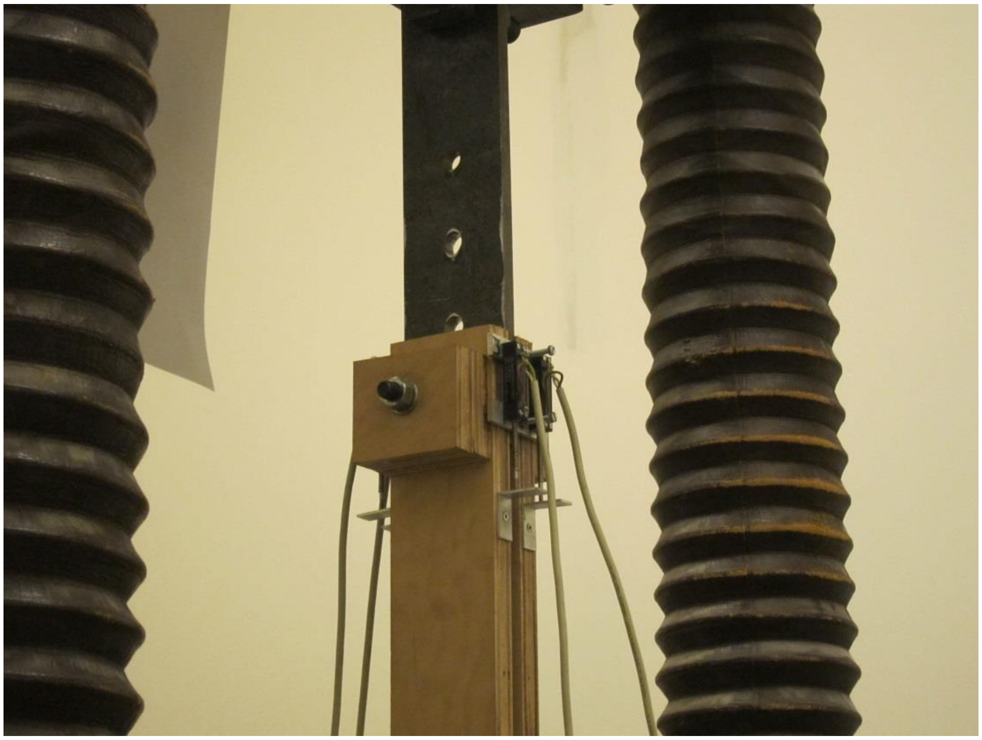
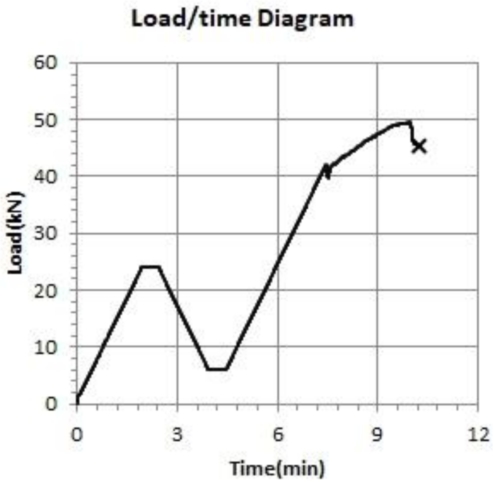


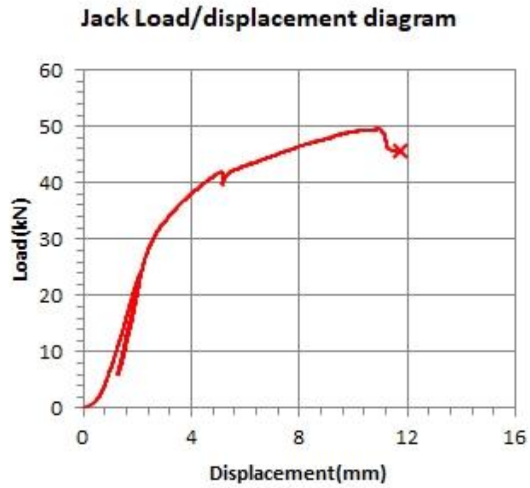
Figure 256 Perspective view nr1. After testing

Data:

T20_A0_N1R_3S	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	49,55	8,38	0,87	10,92	9,93
$F_{0,5}$	45,38	5,00	0,79	7,39	8,45
$F_{failure}$	45,38	9,37	0,86	11,79	10,29

Table 82 Results of specimen T20_A0_N1R_3S





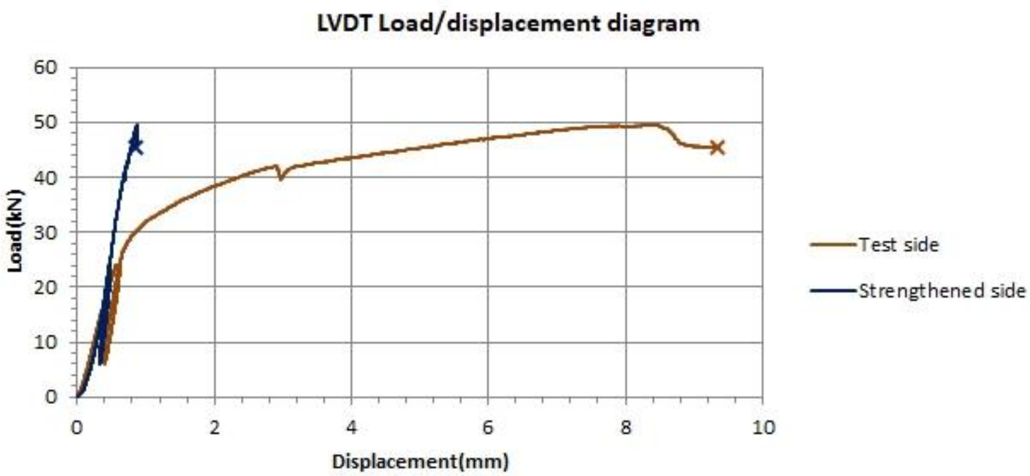


Figure 257 Graphical results of T20_A0_N1R_3S

13.5.2 T20_A0_N1R_4S

Material coding:

Labels Timber	T20_A0_N1R_4Sa	T20_A0_N1R_4Sb
Labels Steel Test side	II-140-46	
Labels Steel Strengthened. side	New(set II)	New(set II)

Table 83 Material coding T20_A0_N1R_4S

Log:

Material: *reused specimen, see previous test for condition*
F_{est}: *50kN*
Displacement controlled speed(1): *0.02mm/s*
Displacement controlled speed(2): *mm/s*

During testing: *went as planned*

Cause of failure: *shear failure*

Additional remarks:

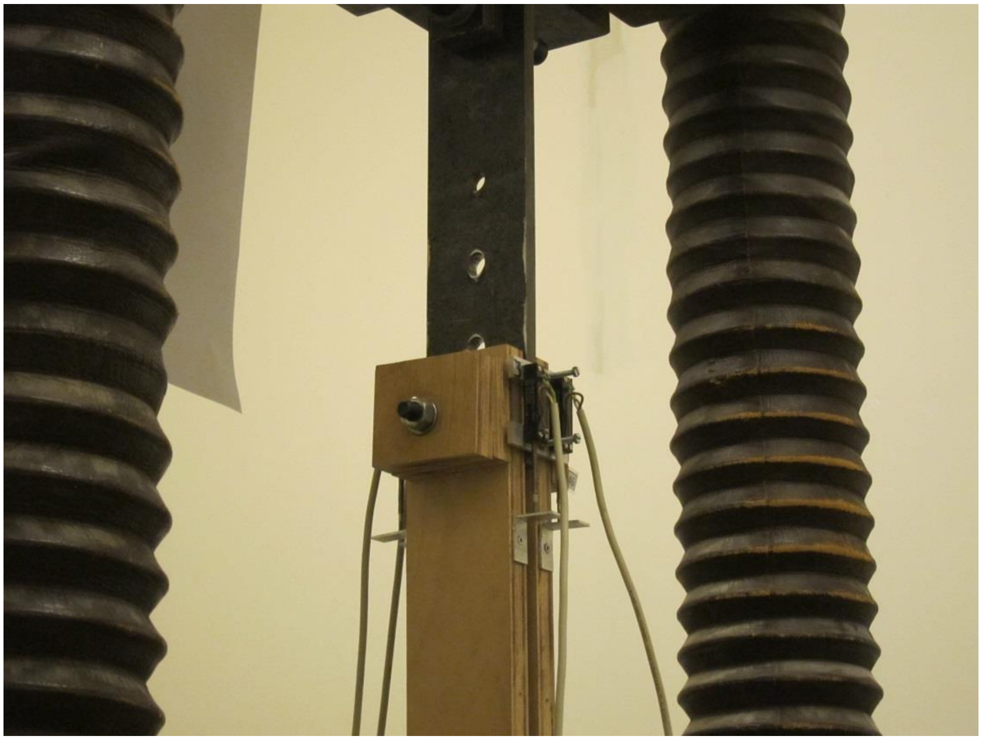


Figure 258 Perspective view nr1. After testing

Data:

T20_A0_N1R_3S	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	57,56	7,77	0,88	10,64	14,17
$F_{0,5}$	52,61	5,00	0,77	7,61	11,64
$F_{failure}$	52,49	8,97	0,89	11,73	15,08

Table 84 Results of specimen T20_A0_N1R_3S

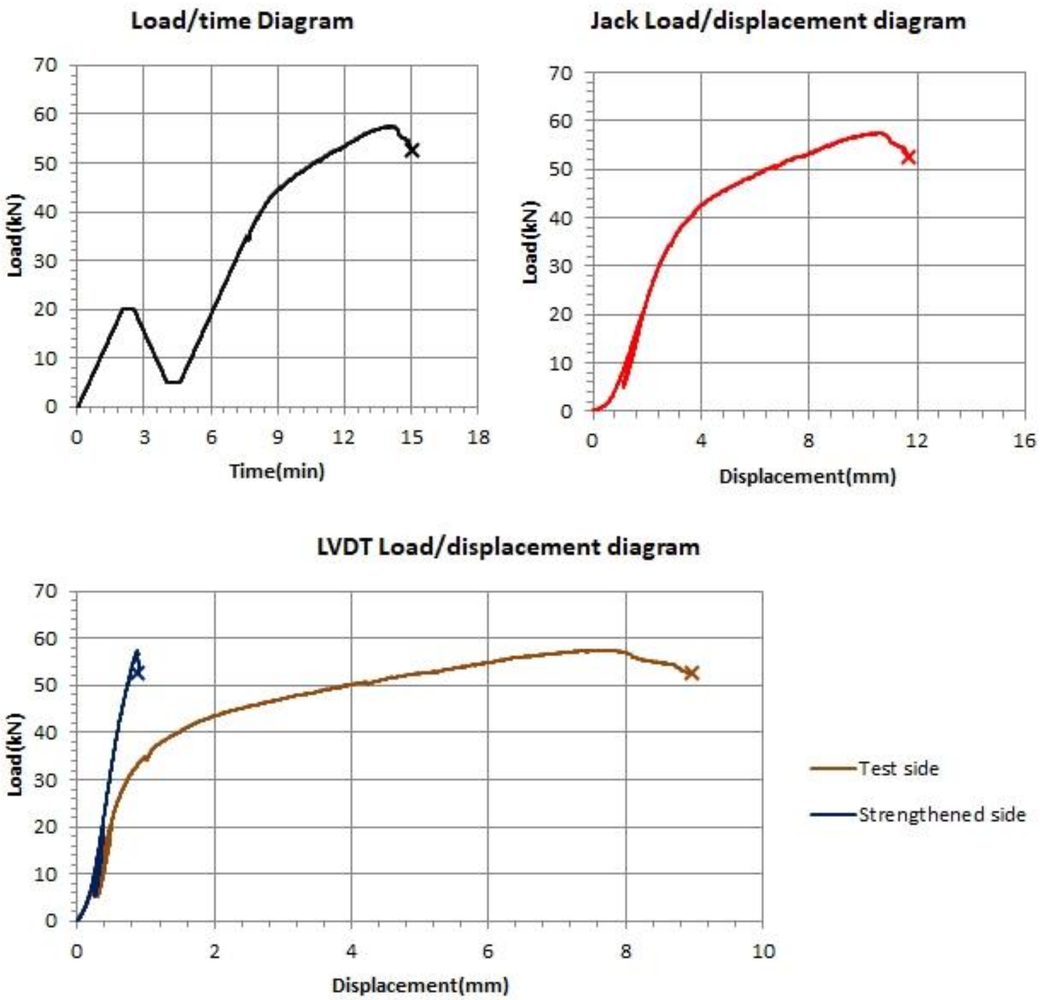


Figure 259 Graphical results of T20_A0_N1R_3S

13.5.3 T20_A0_N1R_5S

Material coding:

Labels Timber	T20_A0_N1R_4Sa	T20_A0_N1R_4Sb
Labels Steel Test side	II-140-47	
Labels Steel Strengthened. side	New(set II)	New(set II)

Table 85 Material coding T20_A0_N1R_5S

Log:

Material: *reused specimen, see previous test for condition*
F_{est}: *60kN*
Displacement controlled speed(1): *0.0275mm/s*
Displacement controlled speed(2): *-mm/s*

During testing: *as planned*

Cause of failure: *shear failure*

Additional remarks:

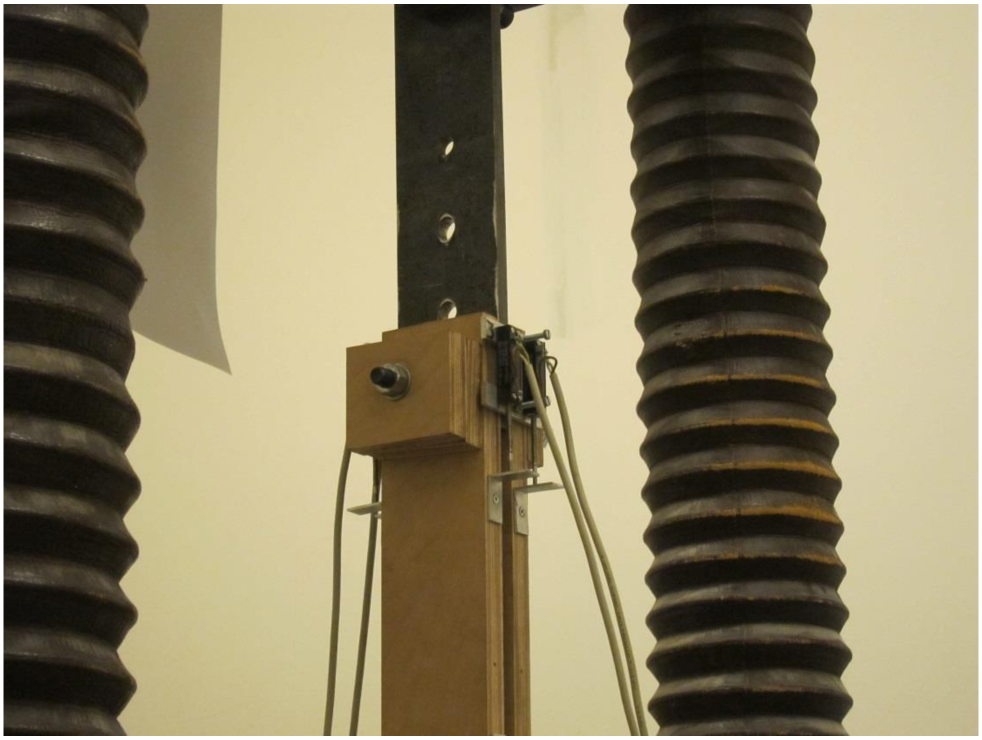


Figure 260 Perspective view nr1. After testing

Data:

T20_A0_N1R_5S	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	59,28	9,35	0,98	12,39	12,63
$F_{0,5}$	52,60	5,00	0,85	7,76	9,82
$F_{failure}$	55,09	10,52	0,98	13,45	13,27

Table 86 Results of specimen T20_A0_N1R_5S

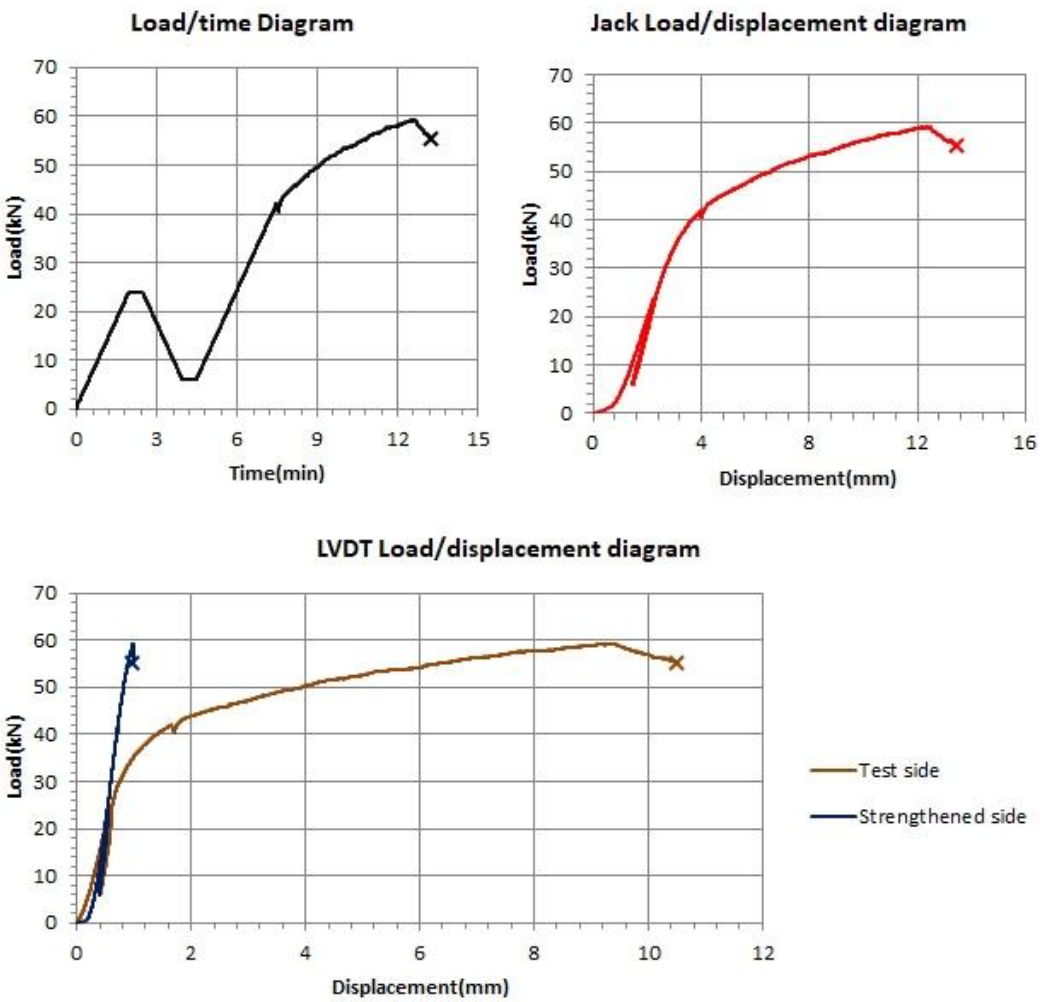


Figure 261 Graphical results of T20_A0_N1R_5S

13.6 T20_A0_N2

Before Testing(pictures test specimen T20_A0_N2_1 shear failure):

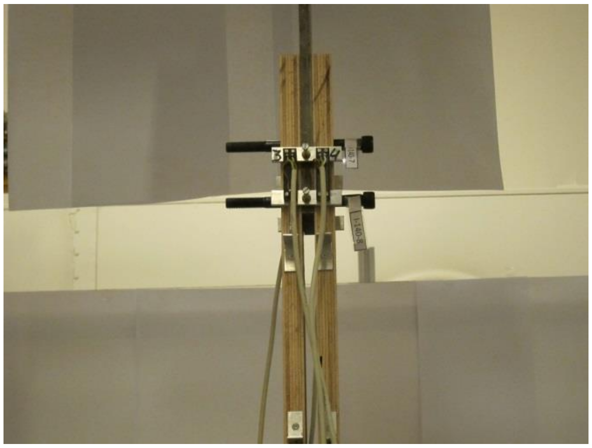


Figure 262 Front view

Figure 263 Perspective view nr. 1

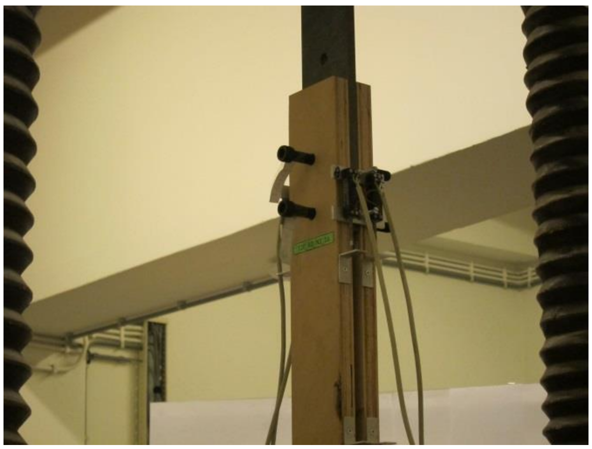


Figure 264 Perspective view nr 2

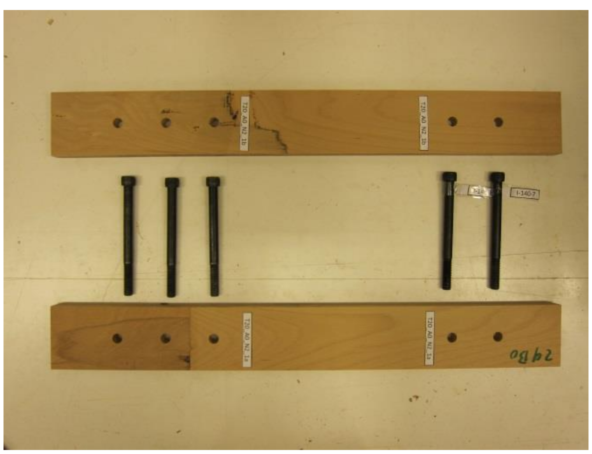


Figure 265 Overview materials

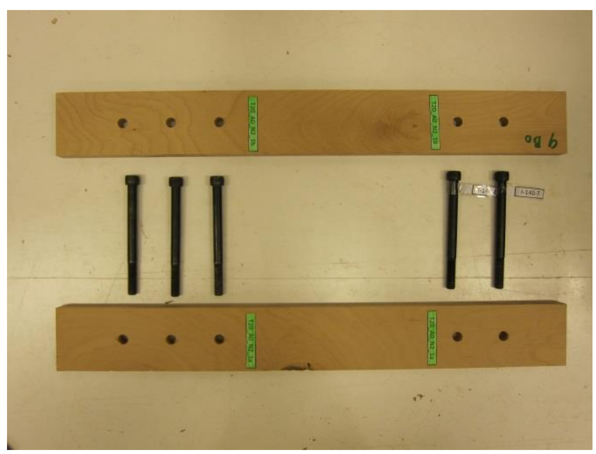


Figure 266 Overview materials

After testing

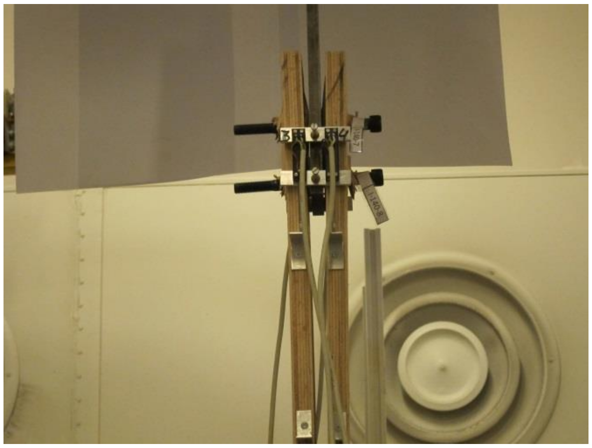


Figure 267 Front view

Figure 268 Perspective view nr. 1

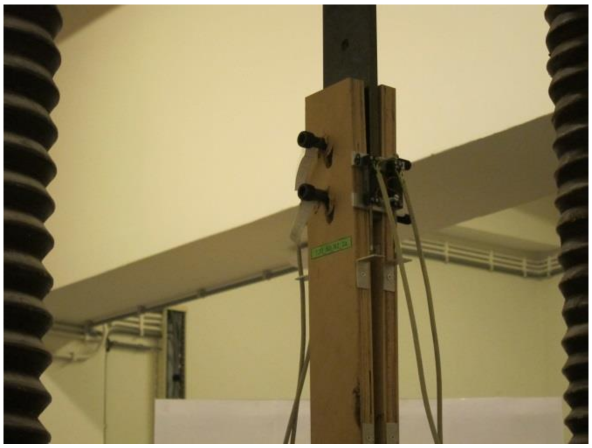


Figure 269 perspective view nr 2

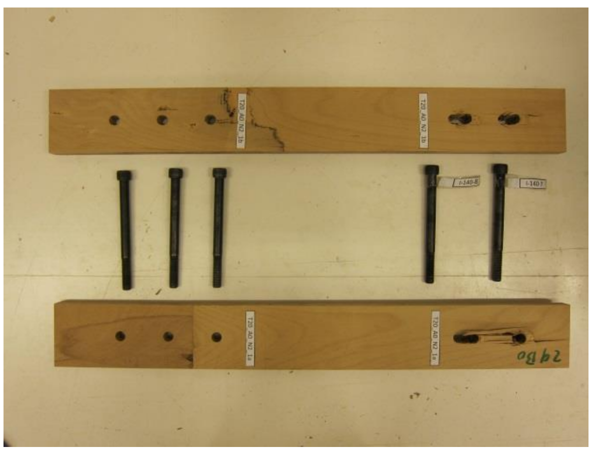


Figure 270 Overview materials

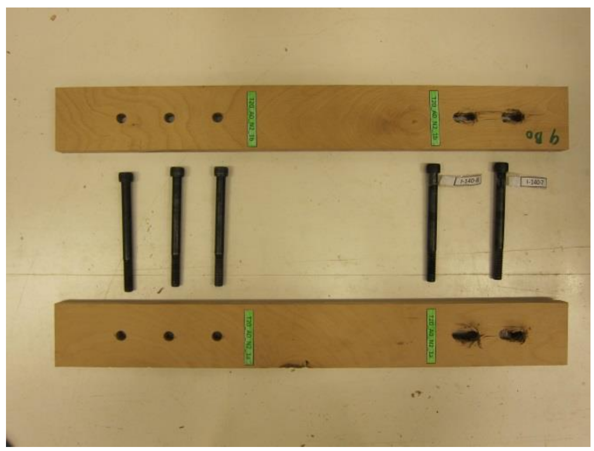


Figure 271 Overview materials

Figure 272 Closeup failure(Surface towards steel plate)

Figure 274 Closeup failure(Surface on the outside)

Figure 273 Closeup failure(Surface towards steel plate)

Figure 275 Closeup failure(Surface on the outside)

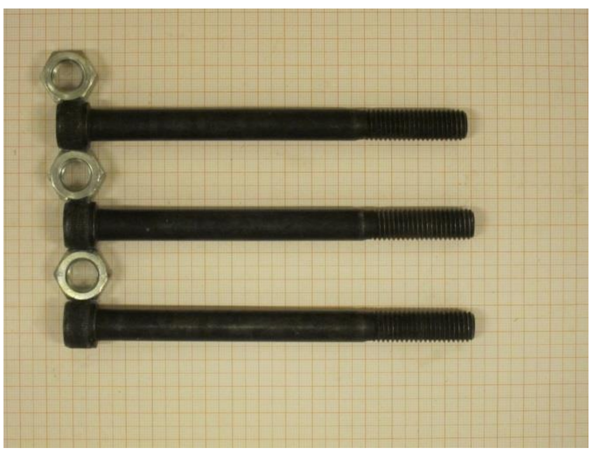


Figure 276 Dowels after testing strengthened side

Figure 277 dowels after testing test side

***Before Testing**(pictures test specimen T20_A0_N2_4 tensile failure):*

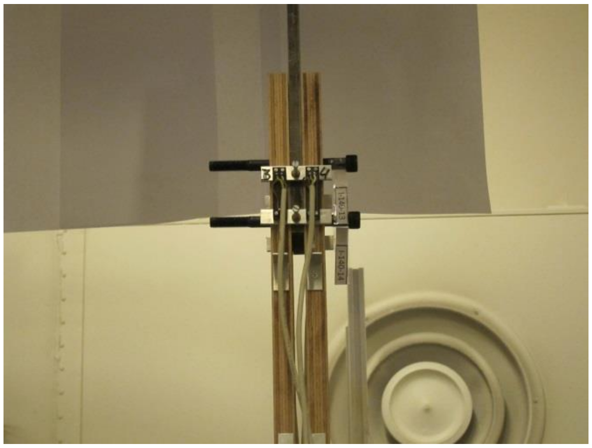


Figure 278 Front view

Figure 279 Perspective view nr. 1

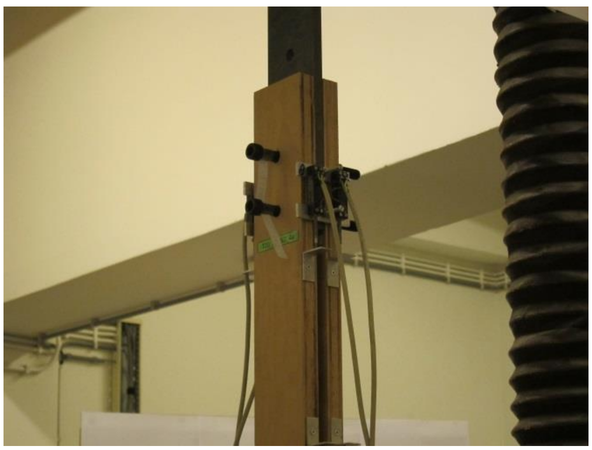


Figure 280 Perspective view nr 2

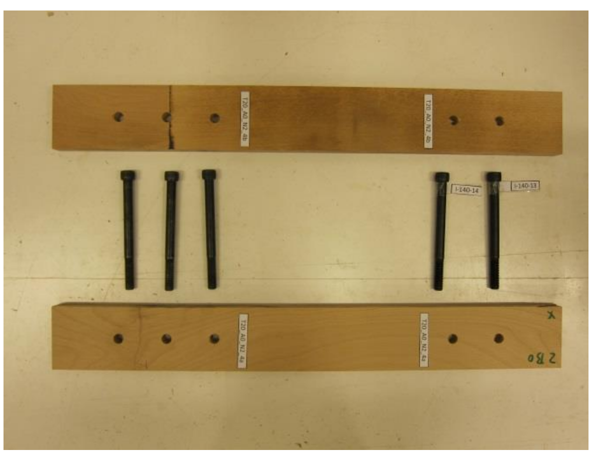


Figure 281 Overview materials

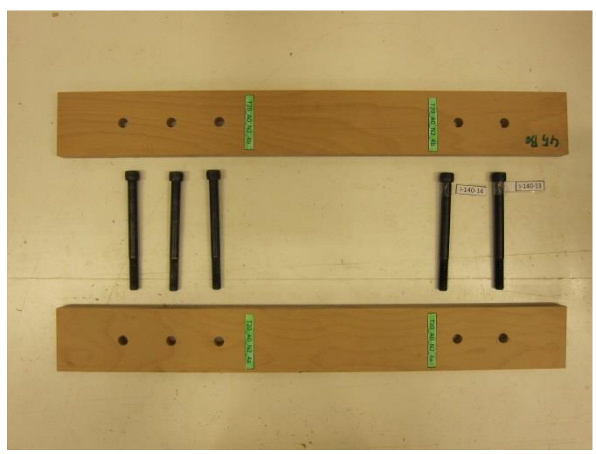


Figure 282 Overview materials

After testing

Figure 283 Front view

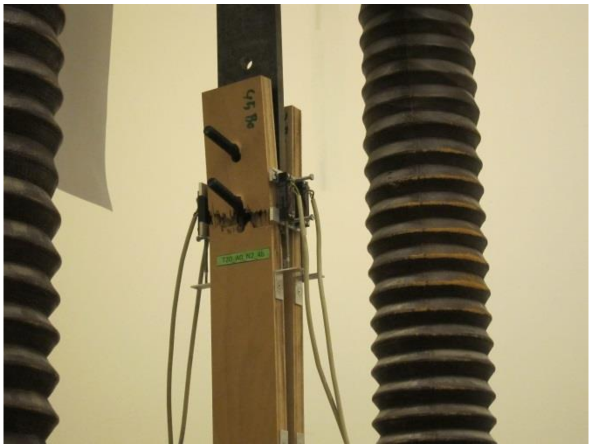


Figure 284 Perspective view nr. 1

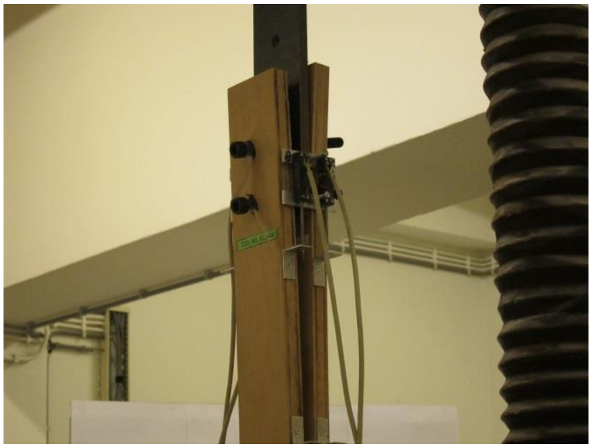


Figure 285 perspective view nr 2

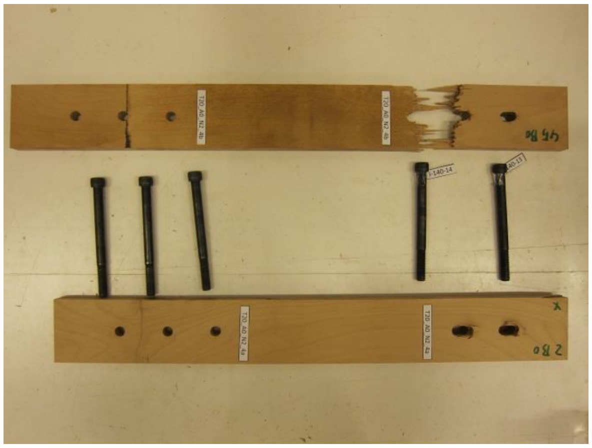


Figure 286 Overview materials

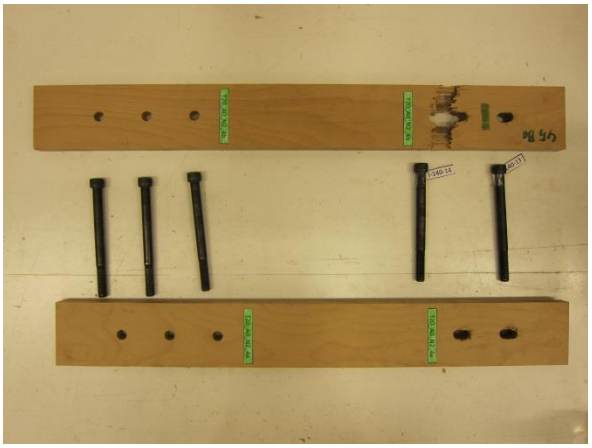


Figure 287 Overview materials

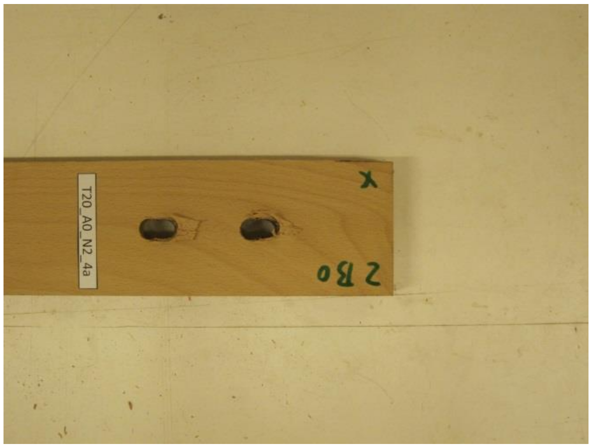


Figure 288 Closeup failure(Surface towards steel plate)

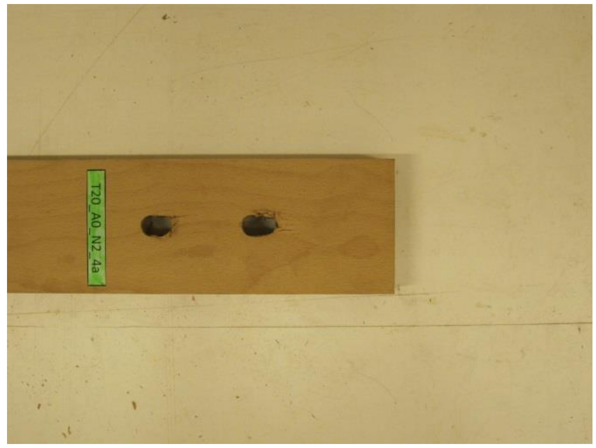


Figure 290 Closeup failure(Surface on the outside)

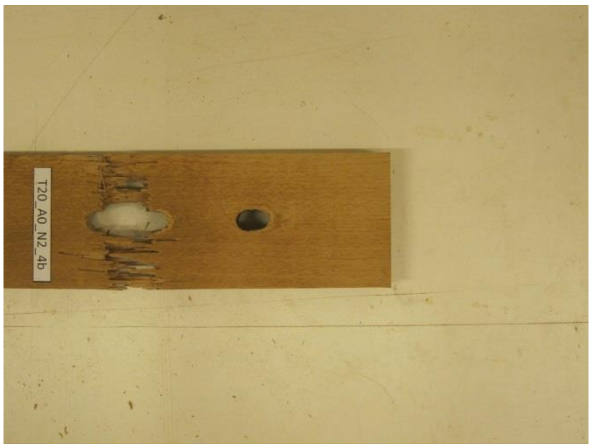


Figure 289 Closeup failure(Surface towards steel plate)

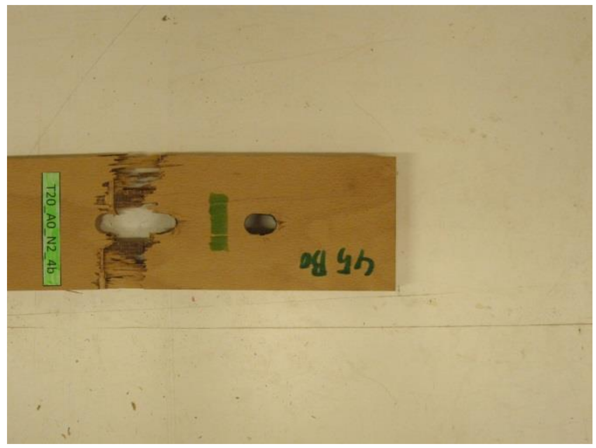


Figure 291 Closeup failure(Surface on the outside)

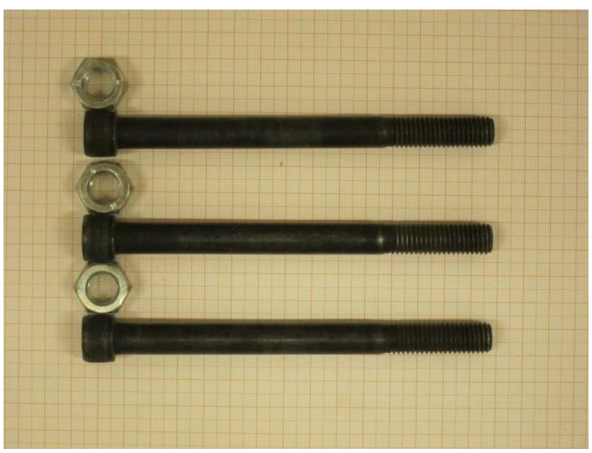


Figure 292 Dowels after testing strengthened side

Figure 293 dowels after testing test side

13.6.1 T20_A0_N2_1

Material coding:

Labels Timber	T20_A0_N2_1a	T20_A0_N2_1b	
Labels Steel Test side	I-140-7	I-140-8	
Labels Steel Strengthened. side	Reused	Reused	Reused

Table 87 Material coding T20_A0_N2_1

Log:

Material: *specimen contains a void in cross layer over full width. Specimen b is a clear specimen.*
F_{est}: *100kN*
Displacement controlled speed(1): *0.03mm/s*
Displacement controlled speed(2): *-mm/s*

During testing: *went as planned*

Cause of failure: *embedment failure*

Additional remarks:

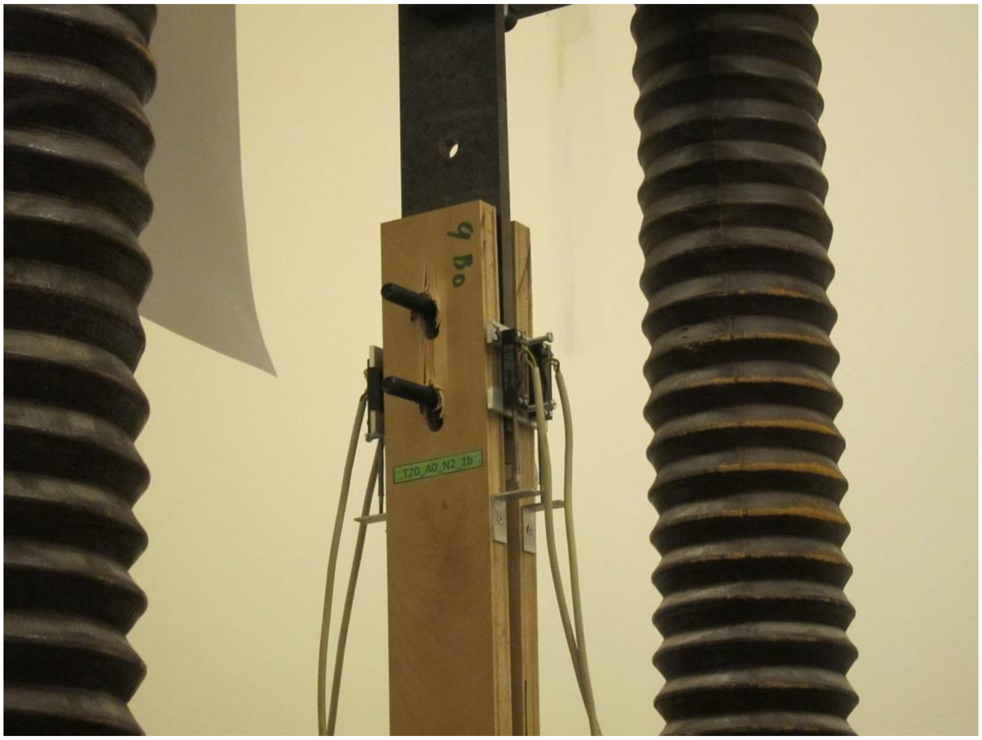


Figure 294 Perspective view nr1. After testing

Data:

T20_A0_N2_1	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	95,21	7,72	1,52	11,66	11,99
$F_{0,5}$	89,46	5,00	1,34	8,63	10,31
$F_{failure}$	74,05	18,22	1,57	21,70	17,57

Table 88 Results of specimen T20_A0_N2_1

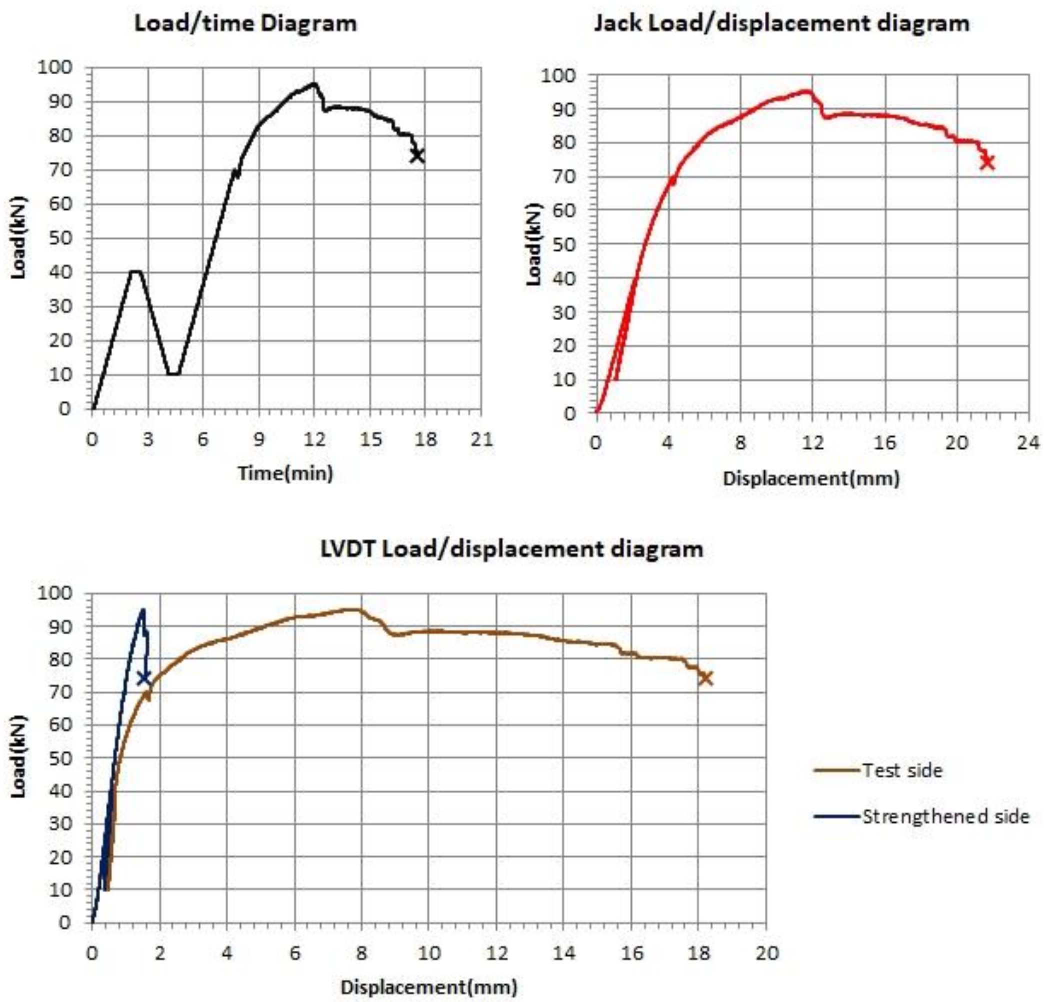


Figure 295 Graphical results of T20_A0_N2_1

13.6.2 T20_A0_N2_2

Material coding:

Labels Timber	T20_A0_N2_2a	T20_A0_N2_2b	
Labels Steel Test side	I-140-9	I-140-10	
Labels Steel Strengthened. side	Reused	Reused	Reused

Table 89 Material coding T20_A0_N2_2

Log:

Material: *In the middle specimen a has a void over full width of the cross layer. Specimen b is a clear specimen*
F_{est}: *100kN*
Displacement controlled speed(1): *0.03mm/s*
Displacement controlled speed(2): *-mm/s*

During testing: *as planned*

Cause of failure: *embedment/shear failure*

Additional remarks: *in between the dowels shear occurred which spalled off some of the timber veneers.*

Figure 296 Perspective view nr1. After testing

Data:

T20_A0_N2_2	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	89,44	9,20	1,79	13,42	12,57
$F_{0,5}$	85,66	5,00	1,68	9,02	10,12
$F_{failure}$	60,01	19,22	1,60	22,65	17,70

Table 90 Results of specimen T20_A0_N2_2

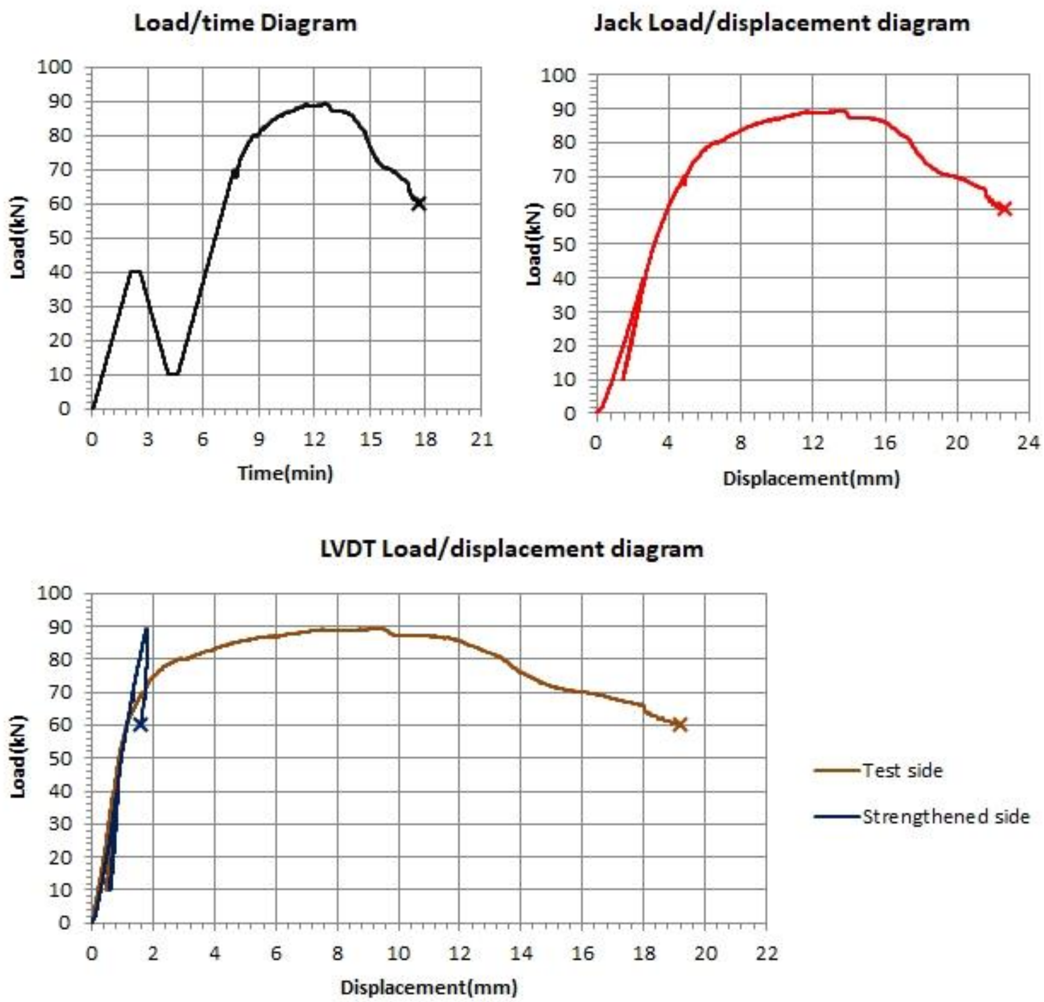


Figure 297 Graphical results of T20_A0_N2_2

13.6.3 T20_A0_N2_3

Material coding:

Labels Timber	T20_A0_N2_3a	T20_A0_N2_3b	
Labels Steel Test side	I-140-11	I-140-12	
Labels Steel Strengthened. side	Reused	Reused	Reused

Table 91 Material coding T20_A0_N2_3

Log:

Material: *clear specimen*

F_{est}: *100kN*
Displacement controlled speed(1): *0.03mm/s*
Displacement controlled speed(2): *-mm/s*

During testing: *as planned*

Cause of failure: *embedment failure*

Additional remarks: *loss of strength due to veneers getting badly damaged*

Figure 298 Perspective view nr1. After testing

Data:

T20_A0_N2_3	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	99,28	8,48	1,42	12,40	12,62
$F_{0,5}$	94,99	5,00	1,29	8,76	10,59
$F_{failure}$	64,64	21,01	1,25	23,93	19,03

Table 92 Results of specimen T20_A0_N2_3

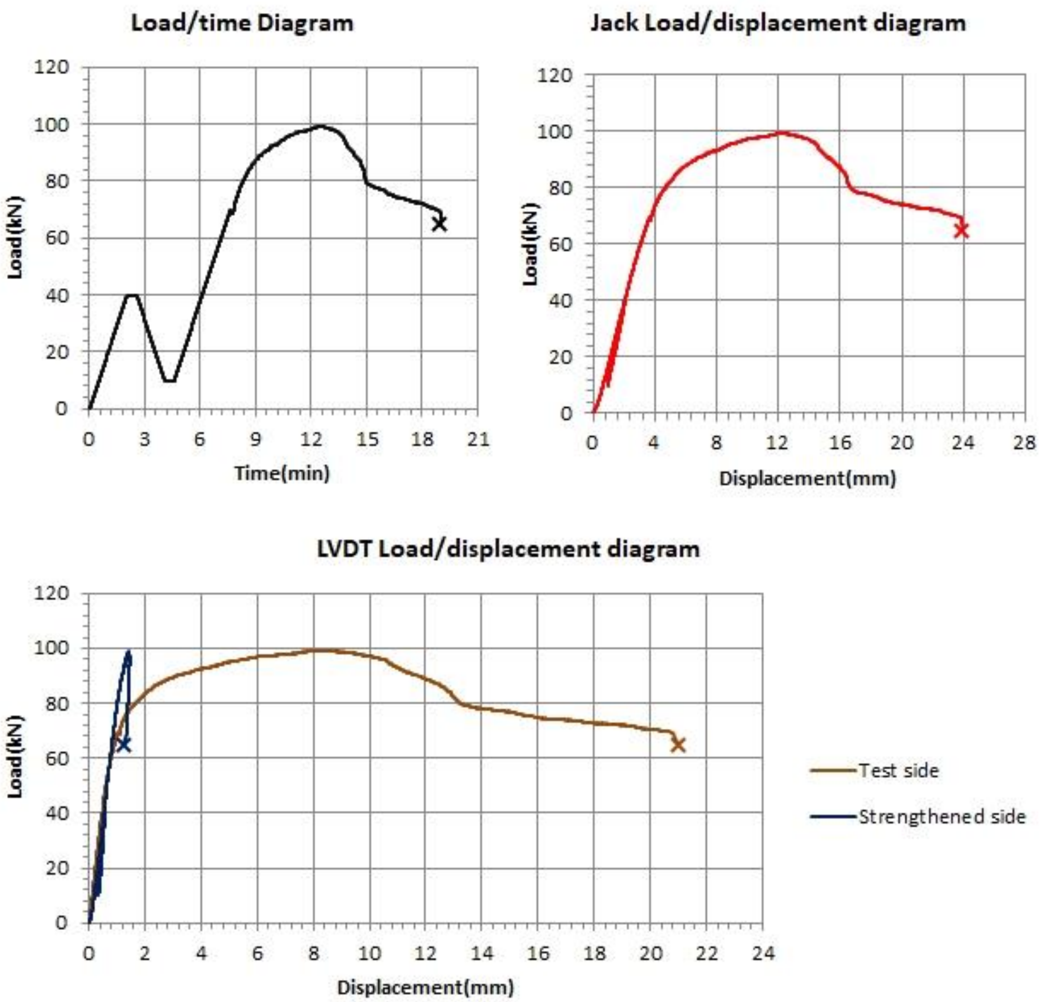


Figure 299 Graphical results of T20_A0_N2_3

13.6.4 T20_A0_N2_4

Material coding:

Labels Timber	T20_A0_N2_4a	T20_A0_N2_4b	
Labels Steel Test side	I-140-13	I-140-14	
Labels Steel Strengthened. side	Reused	Reused	Reused

Table 93 Material coding T20_A0_N2_4

Log:

Material: *small void near lvdt 6 at specimen a. Specimen b clear specimen*
F_{est}: *100kN*
Displacement controlled speed(1): *0.03mm/s*
Displacement controlled speed(2): *mm/s*

During testing: *as planned*

Cause of failure: *tensile failure*

Additional remarks: *specimen failed due to tensile failure which was not expected.*

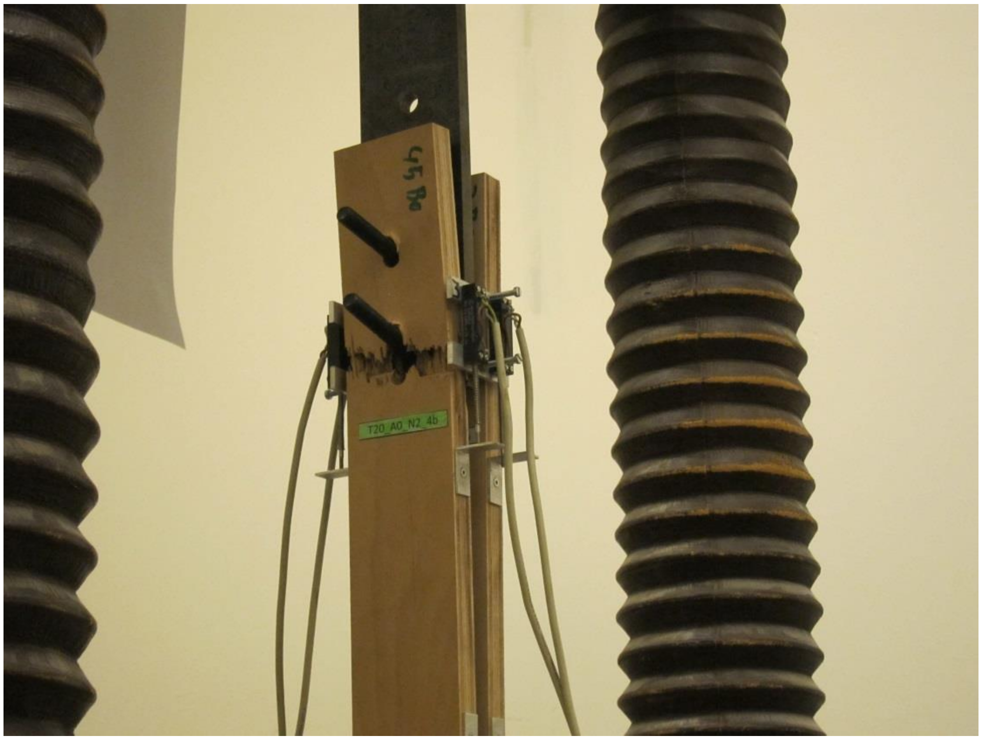
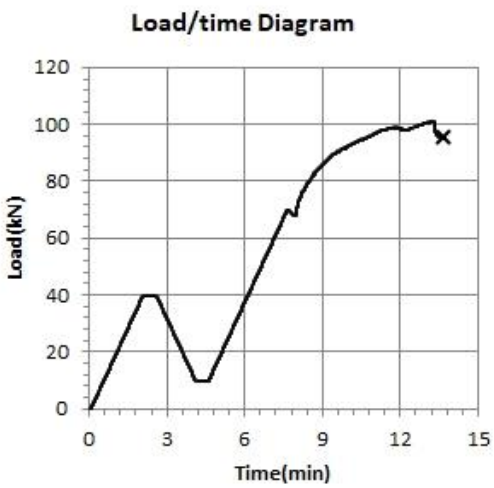


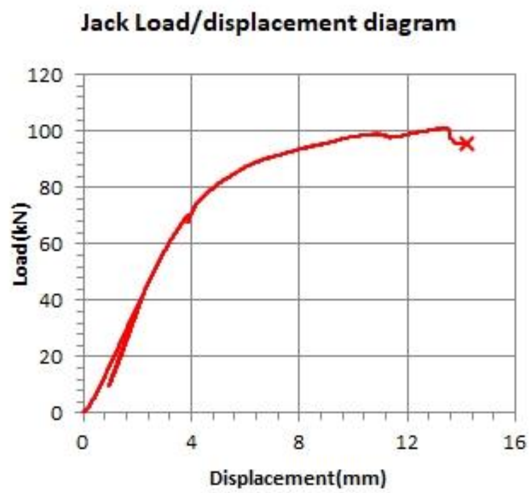
Figure 300 Perspective view nr1. After testing

Data:

T20_A0_N2_4	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	100,98	9,38	1,45	13,40	13,25
$F_{0,5}$	94,99	5,00	1,30	8,68	10,62
$F_{failure}$	95,16	10,34	1,39	14,25	13,72

Table 94 Results of specimen T20_A0_N2_4





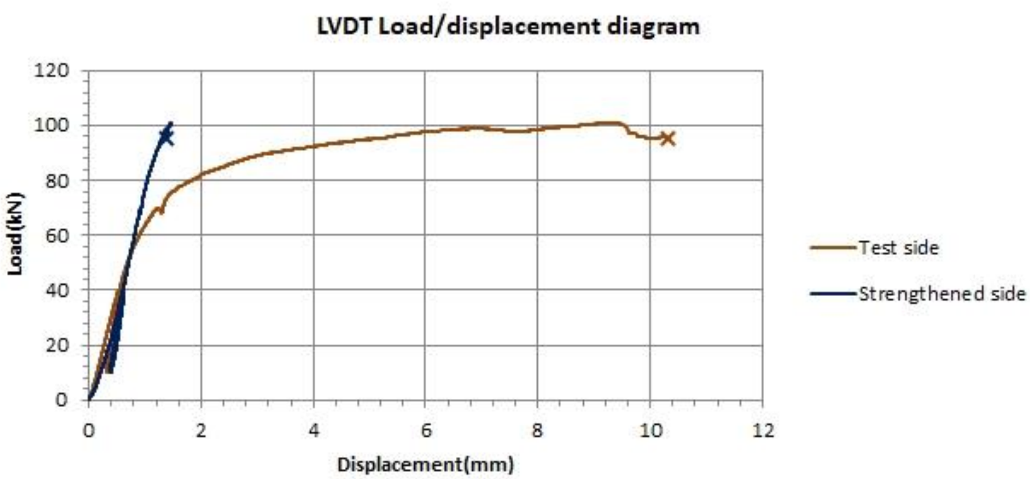


Figure 301 Graphical results of T20_A0_N2_4

13.6.5 T20_A0_N2_5

Material coding:

Labels Timber	T20_A0_N2_5a	T20_A0_N2_5b	
Labels Steel Test side	I-140-15	I-140-16	
Labels Steel Strengthened. side	Reused	Reused	Reused

Table 95 Material coding T20_A0_N2_5

Log:

Material: *clear specimen*

F_{est}: *100kN*

Displacement controlled speed(1): *0.03mm/s*

Displacement controlled speed(2): *mm/s*

During testing: *as planned*

Cause of failure: *tensile failure*

Additional remarks: *The gap between timber and steel plate differed from one another right before failure.*

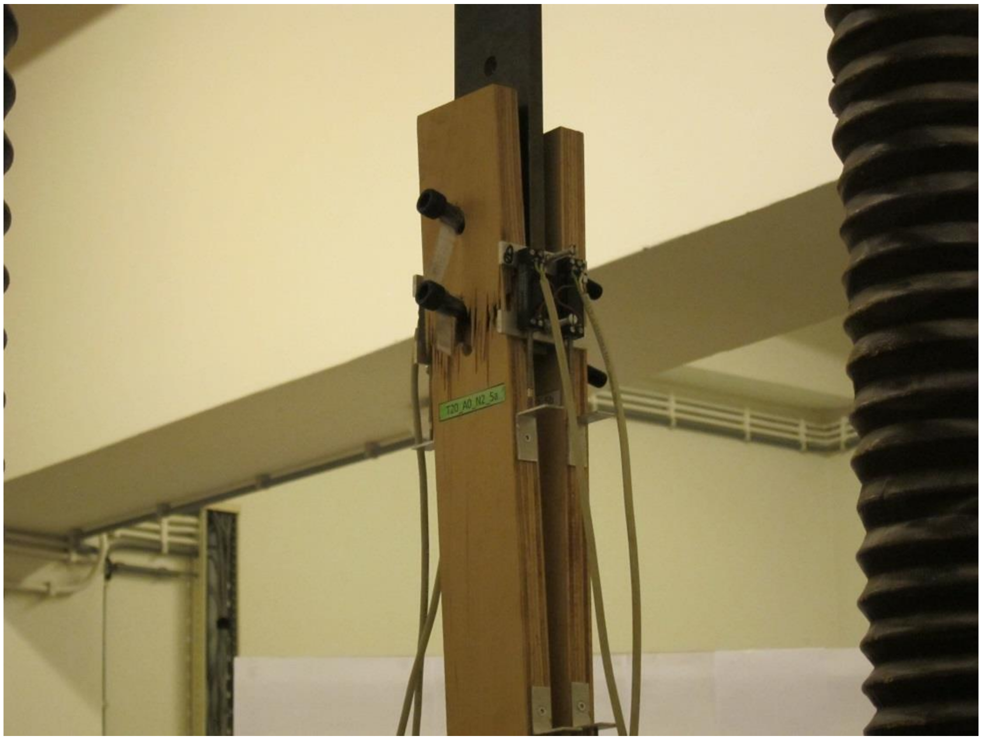


Figure 302 Perspective view nr2. After testing

Data:

T20_A0_N2_5	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	101,75	7,95	1,75	12,51	12,18
$F_{0,5}$	96,72	5,00	1,60	9,29	10,38
$F_{failure}$	100,13	8,28	1,79	12,76	12,31

Table 96 Results of specimen T20_A0_N2_5

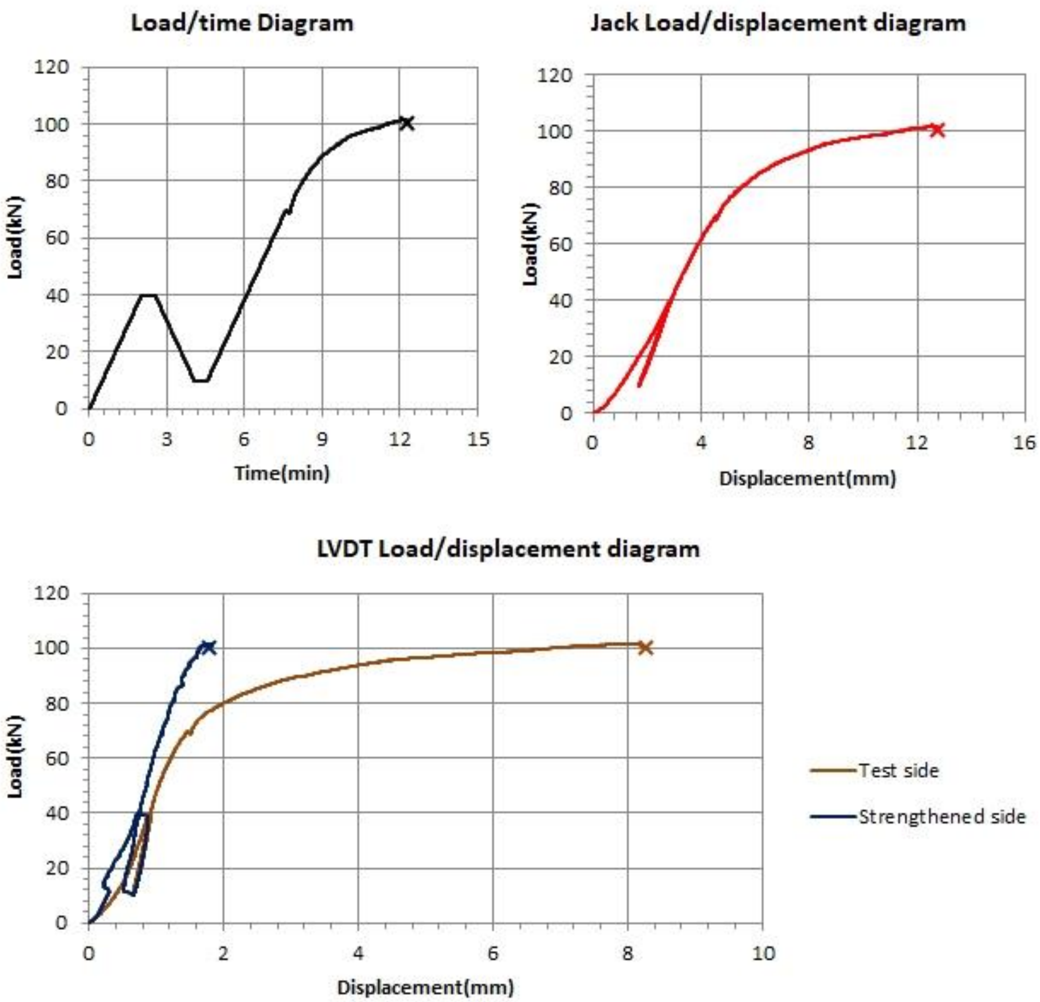


Figure 303 Graphical results of T20_A0_N2_5

13.7 T20_A0_N2R

<u>Before Testing</u>(pictures test specimen T20_A0_N2R_1 shear failure)<u>:</u>

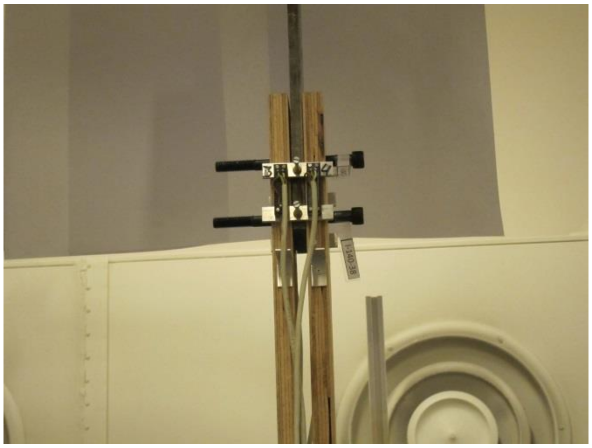


Figure 304 Front view

Figure 305 Perspective view nr. 1

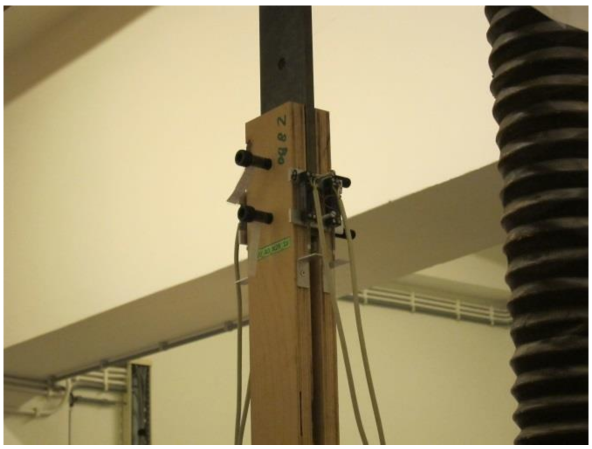


Figure 306 Perspective view nr 2

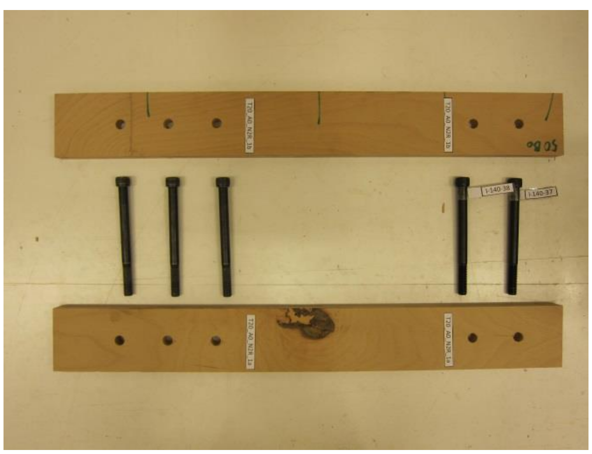


Figure 307 Overview materials

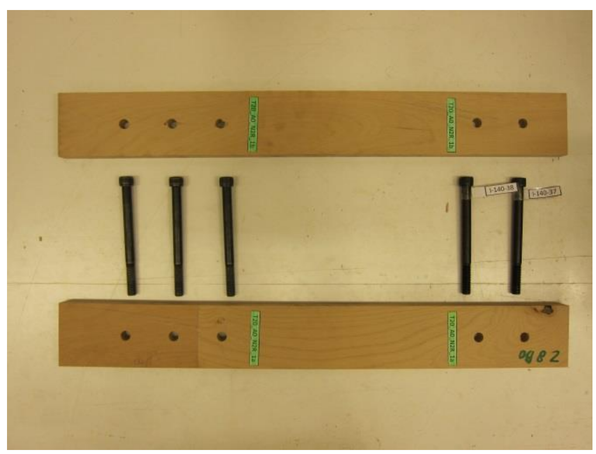


Figure 308 Overview materials

After testing

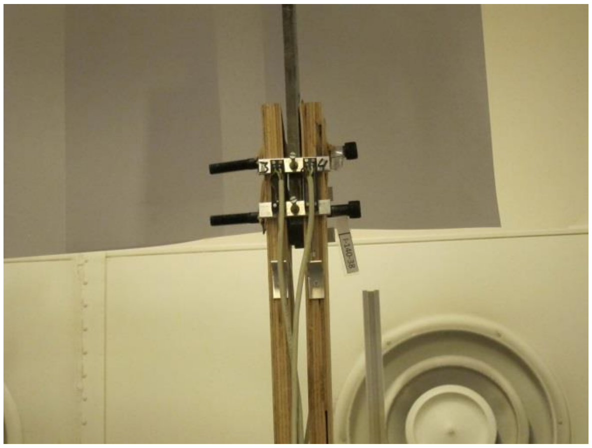


Figure 309 Front view


Figure 310 Perspective view nr. 1

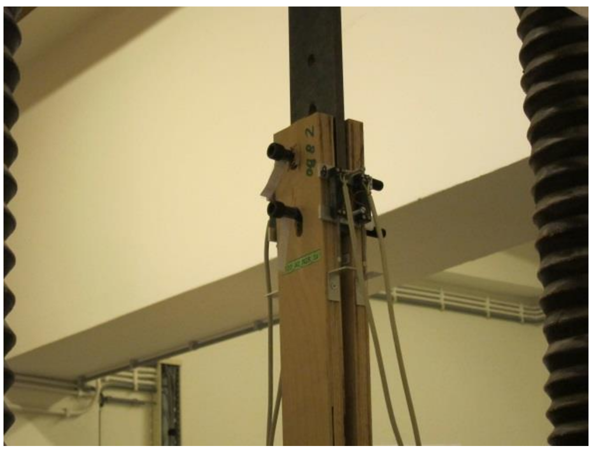


Figure 311 perspective view nr 2

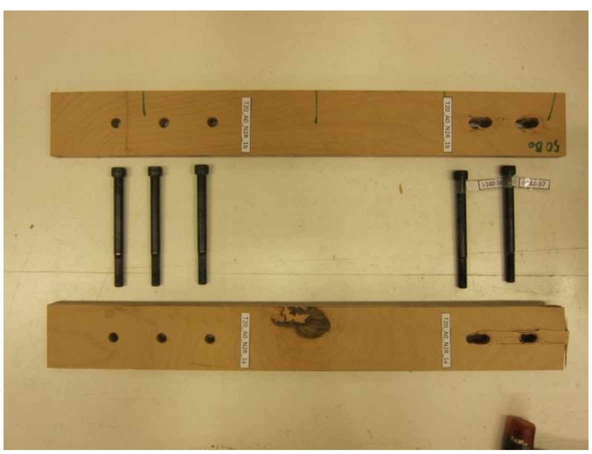


Figure 312 Overview materials

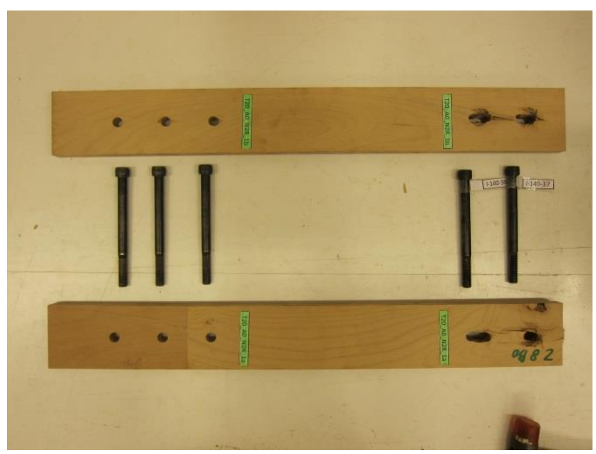


Figure 313 Overview materials

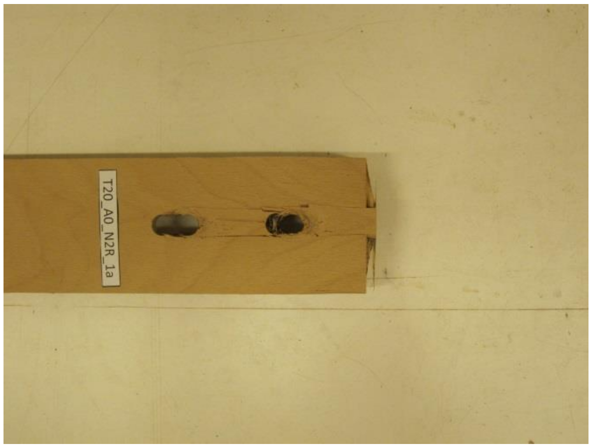


Figure 314 Closeup failure(Surface towards steel plate)

Figure 316 Closeup failure(Surface on the outside)

Figure 315 Closeup failure(Surface towards steel plate)

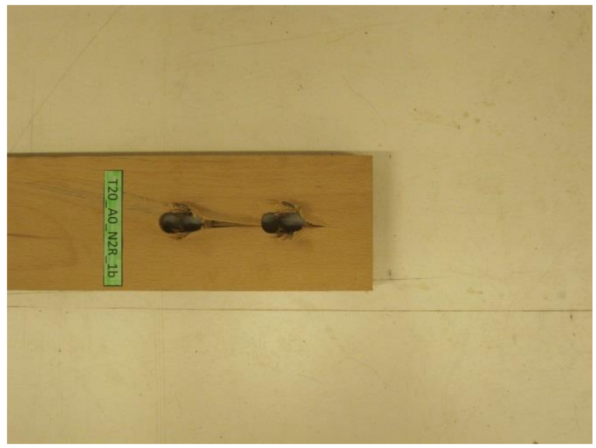


Figure 317 Closeup failure(Surface on the outside)

Figure 318 Dowels after testing strengthened side

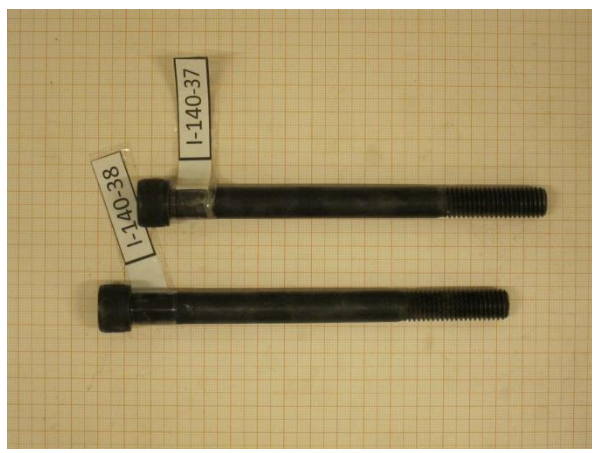


Figure 319 dowels after testing test side

<u>Before Testing</u>(pictures test specimen T20_A0_N2R_3 tensile failure)<u>:</u>

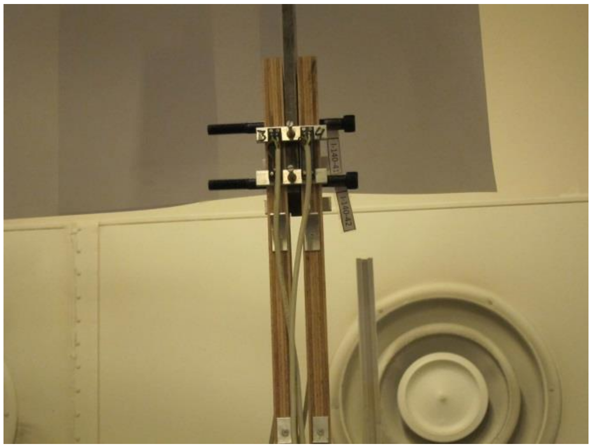


Figure 320 Front view

Figure 321 Perspective view nr. 1

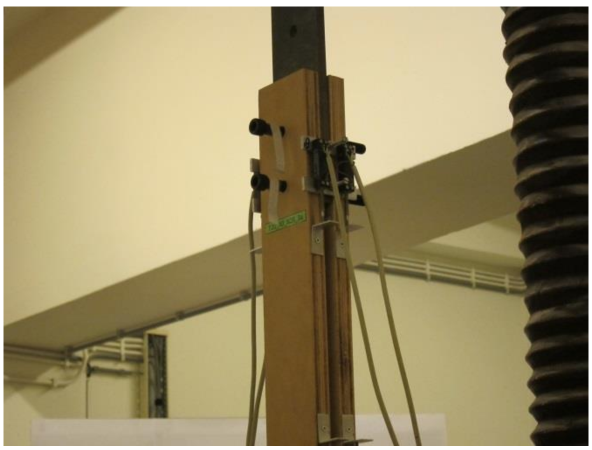


Figure 322 Perspective view nr 2

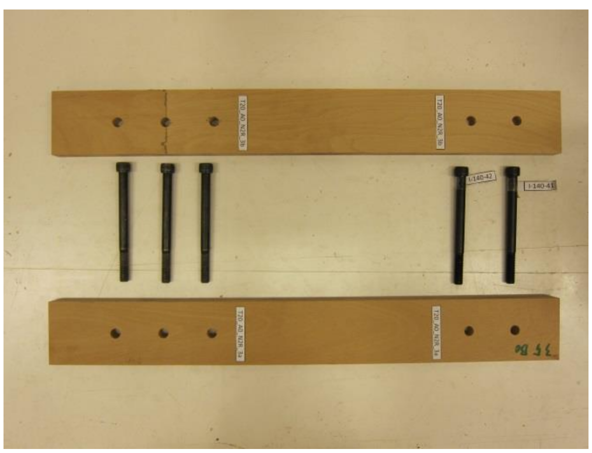


Figure 323 Overview materials

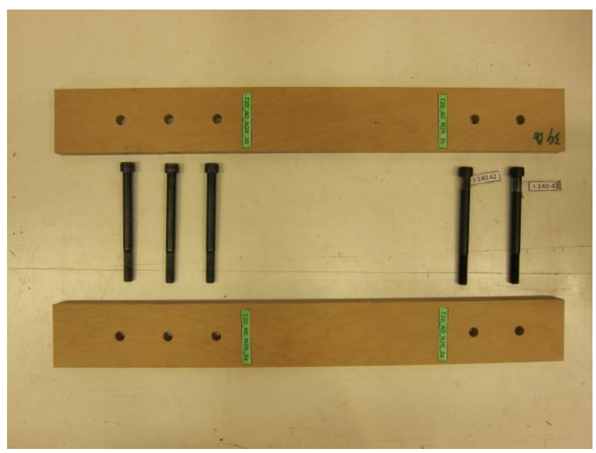


Figure 324 Overview materials

After testing

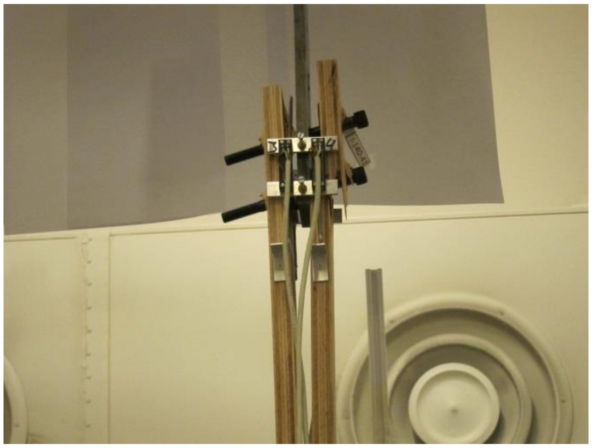


Figure 325 Front view

Figure 326 Perspective view nr. 1

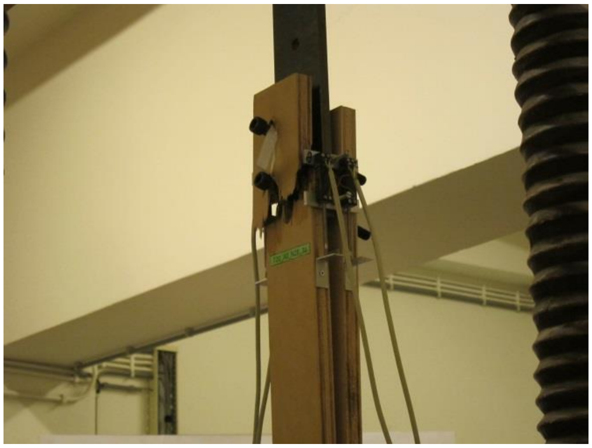


Figure 327 perspective view nr 2

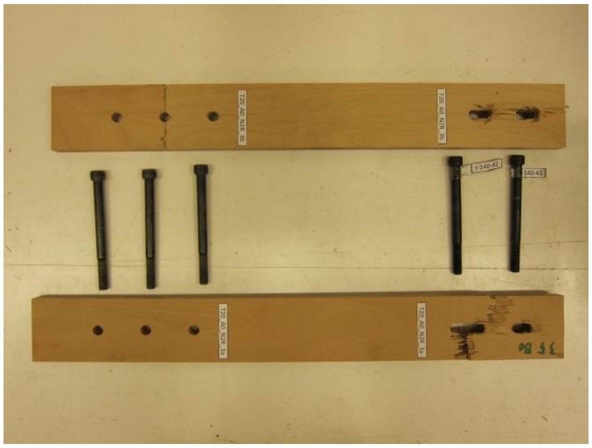


Figure 328 Overview materials

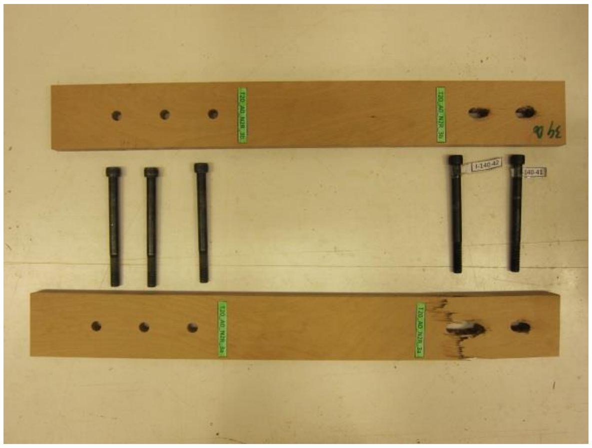


Figure 329 Overview materials

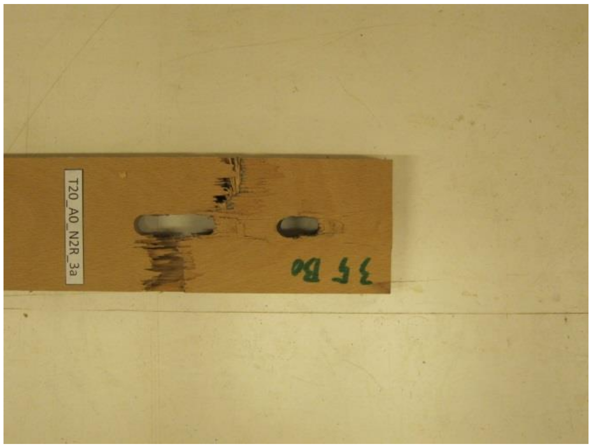


Figure 330 Closeup failure(Surface towards steel plate)

Figure 332 Closeup failure(Surface on the outside)

Figure 331 Closeup failure(Surface towards steel plate)

Figure 333 Closeup failure(Surface on the outside)

Figure 334 Dowels after testing strengthened side

Figure 335 dowels after testing test side

13.7.1 T20_A0_N2R_1

Material coding:

Labels Timber	T20_A0_N2R_1a	T20_A0_N2R_1b	
Labels Steel Test side	I-140-37	I-140-38	
Labels Steel Strengthened. side	Reused	Reused	Reused

Table 97 Material coding T20_A0_N2R_1

Log:

Material: *Specimen a large void present with a width of 4cm through cross layer.*
F_{est}: *100kN*
Displacement controlled speed(1): *0.03mm/s*
Displacement controlled speed(2): *-mm/s*

During testing: *as planned*

Cause of failure: *shear failure*

Additional remarks:

Figure 336 Perspective view nr1. After testing

Data:

T20_A0_N2R_1	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	88,39	7,09	1,27	10,93	11,25
$F_{0,5}$	85,64	5,00	1,21	8,72	10,02
$F_{failure}$	68,10	17,26	1,23	20,50	16,57

Table 98 Results of specimen T20_A0_N2R_1

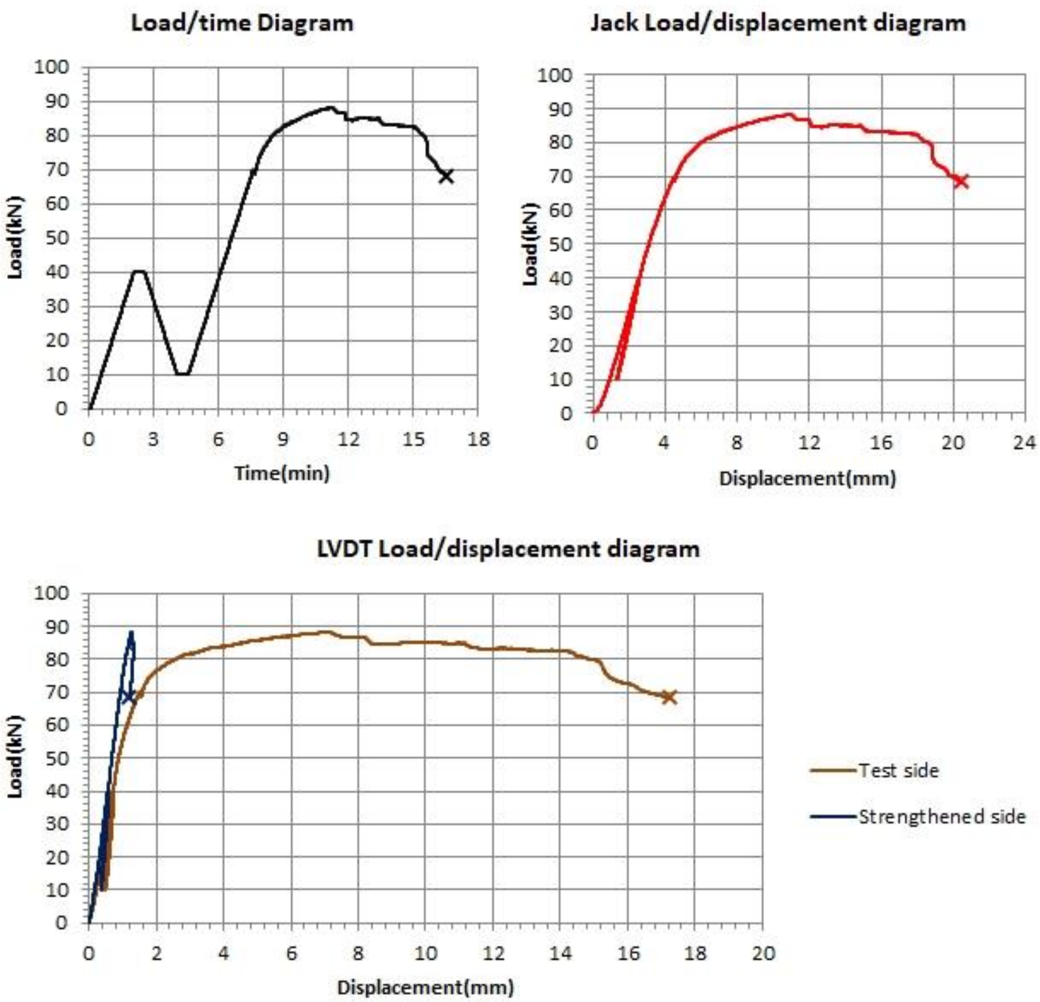


Figure 337 Graphical results of T20_A0_N2R_1

13.7.2 T20_A0_N2R_2

Material coding:

Labels Timber	T20_A0_N2R_2a	T20_A0_N2R_2b	
Labels Steel Test side	I-140-39	I-140-40	
Labels Steel Strengthened. side	Reused	Reused	Reused

Table 99 Material coding T20_A0_N2R_2

Log:

Material: *Knot in specimen b on strengthened specimen, overall clear specimen*
F_{est}: *100kN*
Displacement controlled speed(1): *0.03mm/s*
Displacement controlled speed(2): *mm/s*

During testing: *as planned*

Cause of failure: *shear failure*

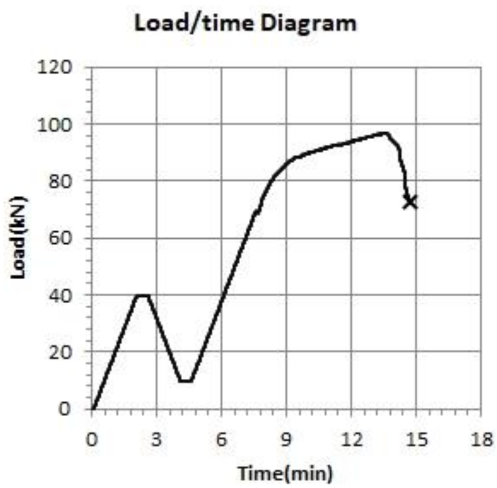
Additional remarks:

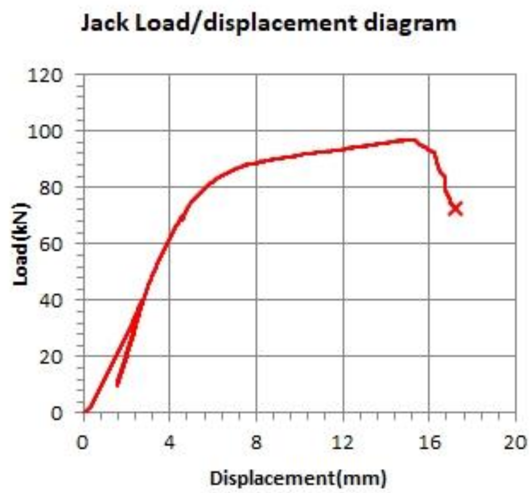
Figure 338 Perspective view nr1. After testing

Data:

T20_A0_N2R_2	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	97,06	10,98	1,64	15,26	13,65
$F_{0,5}$	90,06	5,00	1,44	8,90	10,11
$F_{failure}$	72,46	13,71	1,52	17,27	14,77

Table 100 Results of specimen T20_A0_N2R_2





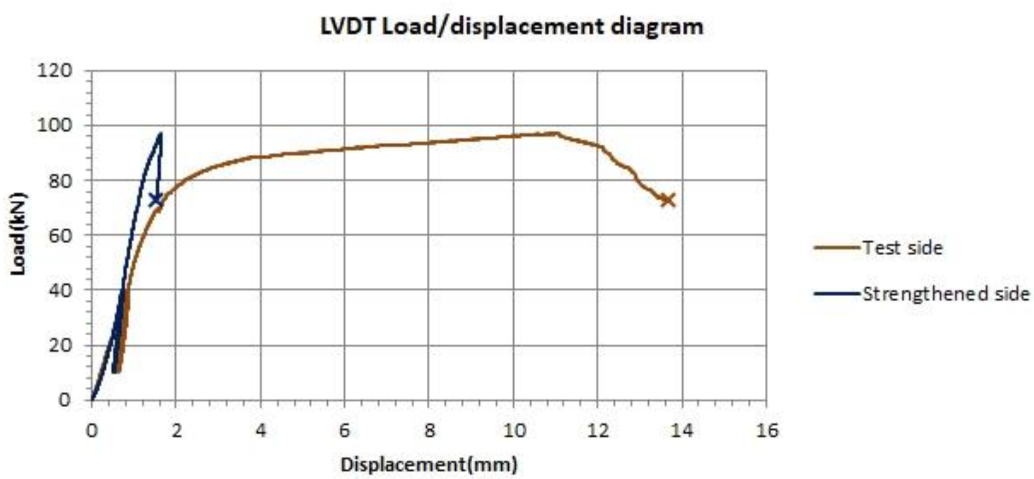


Figure 339 Graphical results of T20_A0_N2R_2

13.7.3 *T20_A0_N2R_3*

Material coding:

Labels Timber	T20_A0_N2R_3a	T20_A0_N2R_3b	
Labels Steel Test side	I-140-41	I-140-42	
Labels Steel Strengthened. side	Reused	Reused	Reused

Table 101 Material coding T20_A0_N2R_3

Log:

Material: *Clear specimen*

F_{est}: *100kN*
Displacement controlled speed(1): *0.03mm/s*
Displacement controlled speed(2): *mm/s*

During testing: *as planned*

Cause of failure: *tensile failure*

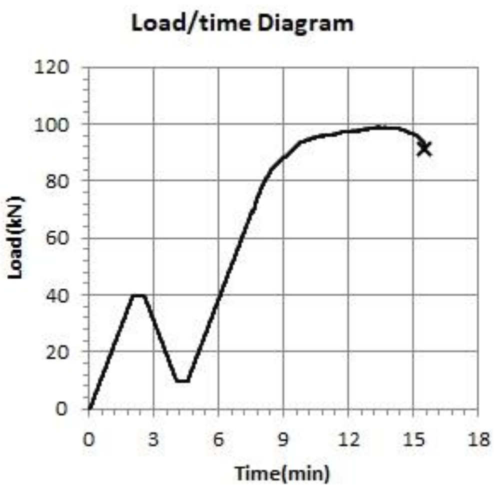
Additional remarks:

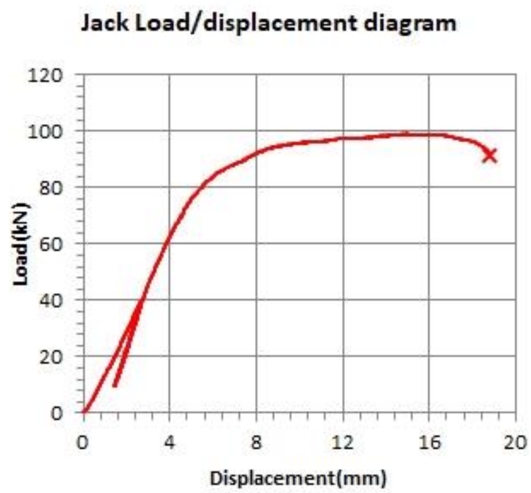
Figure 340 Perspective view nr1. After testing

Data:

T20_A0_N2R_3	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	99,06	10,52	1,58	14,79	13,33
$F_{0,5}$	94,56	5,00	1,42	8,99	10,11
$F_{failure}$	90,89	14,68	1,59	18,78	15,55

Table 102 Results of specimen T20_A0_N2R_3





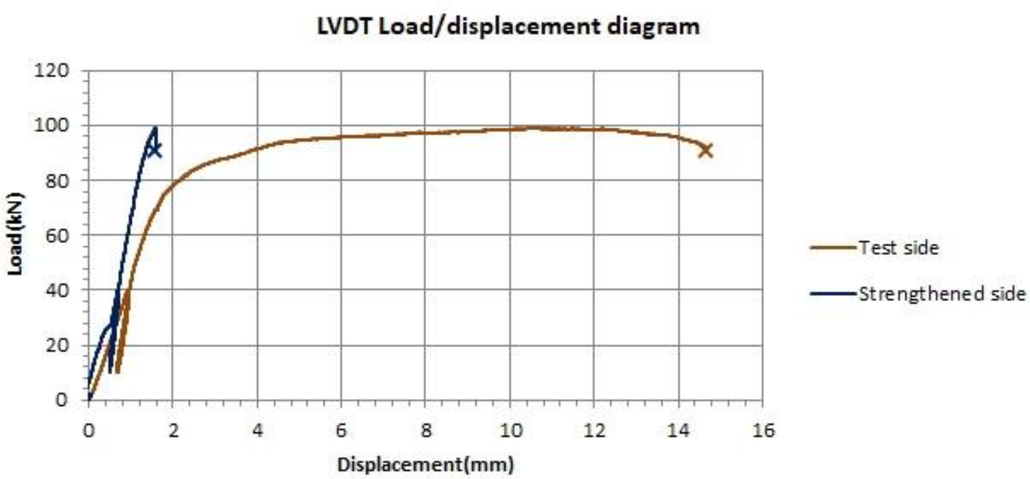


Figure 341 Graphical results of T20_A0_N2R_3

13.7.4 *T20_A0_N2R_4*

Material coding:

Labels Timber	T20_A0_N2R_4a	T20_A0_N2R_4b	
Labels Steel Test side	I-140-43	I-140-44	
Labels Steel Strengthened. side	Reused	Reused	Reused

Table 103 Material coding T20_A0_N2R_4

Log:

Material: *small void present in specimen a*

F_{est}: *100kN*

Displacement controlled speed(1): *0.03mm/s*

Displacement controlled speed(2): *-mm/s*

During testing: as planned

Cause of failure: *Splitting failure*

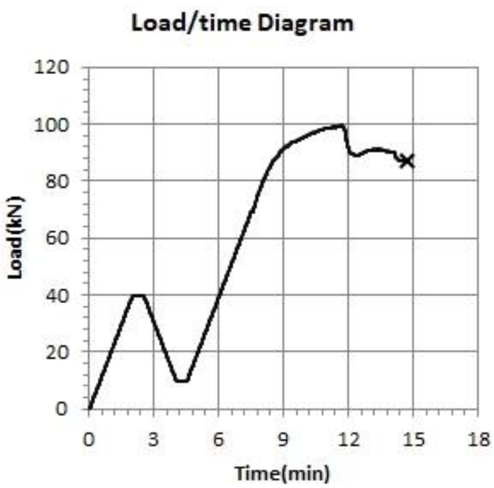
Additional remarks:

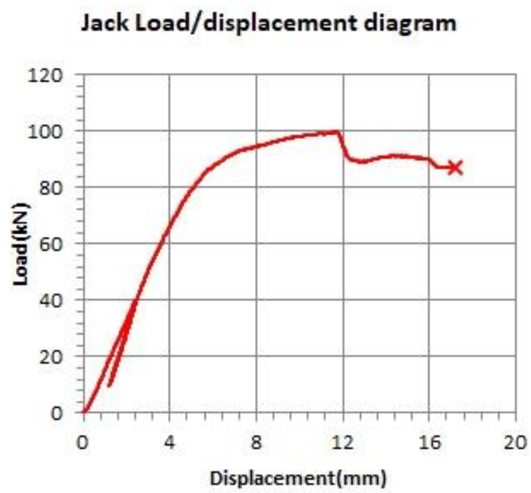
Figure 342 Perspective view nr1. After testing

Data:

T20_A0_N2R_4	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	99,70	7,23	1,70	11,65	11,72
$F_{0,5}$	97,21	5,01	1,63	9,30	10,41
$F_{failure}$	86,87	13,12	1,69	17,21	14,80

Table 104 Results of specimen T20_A0_N2R_4





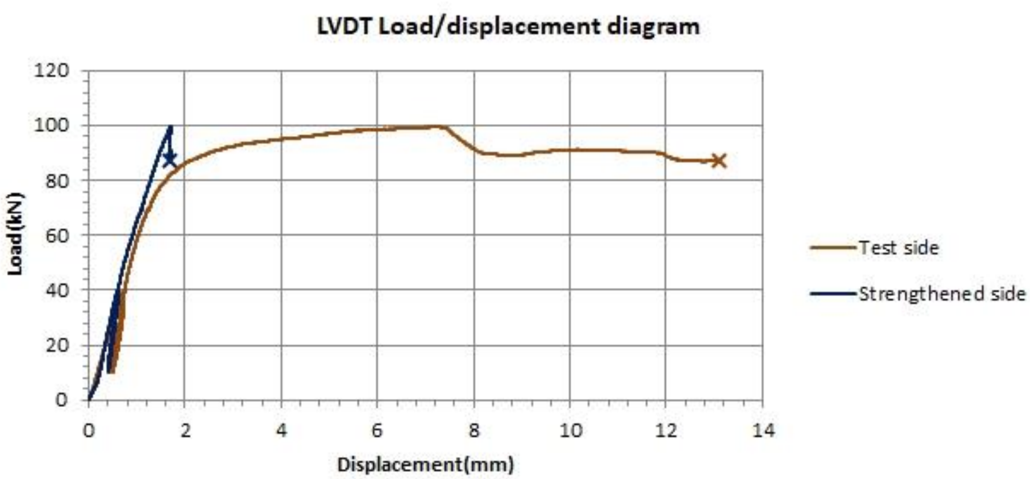


Figure 343 Graphical results of T20_A0_N2R_4

13.7.5 T20_A0_N2R_5

Material coding:

Labels Timber	T20_A0_N2R_4a	T20_A0_N2R_4b	
Labels Steel Test side	I-140-45	I-140-46	
Labels Steel Strengthened. side	Reused	Reused	Reused

Table 105 Material coding T20_A0_N2R_5

Log:

<u>Material</u>: *clear specimen*

<u>F_{est}:</u> *100kN*

<u>Displacement controlled speed(1):</u> *0.03mm/s*

<u>Displacement controlled speed(2):</u> *mm/s*

<u>During testing</u>: *as planned*

<u>Cause of failure:</u> *Shear failure*

<u>Additional remarks:</u>

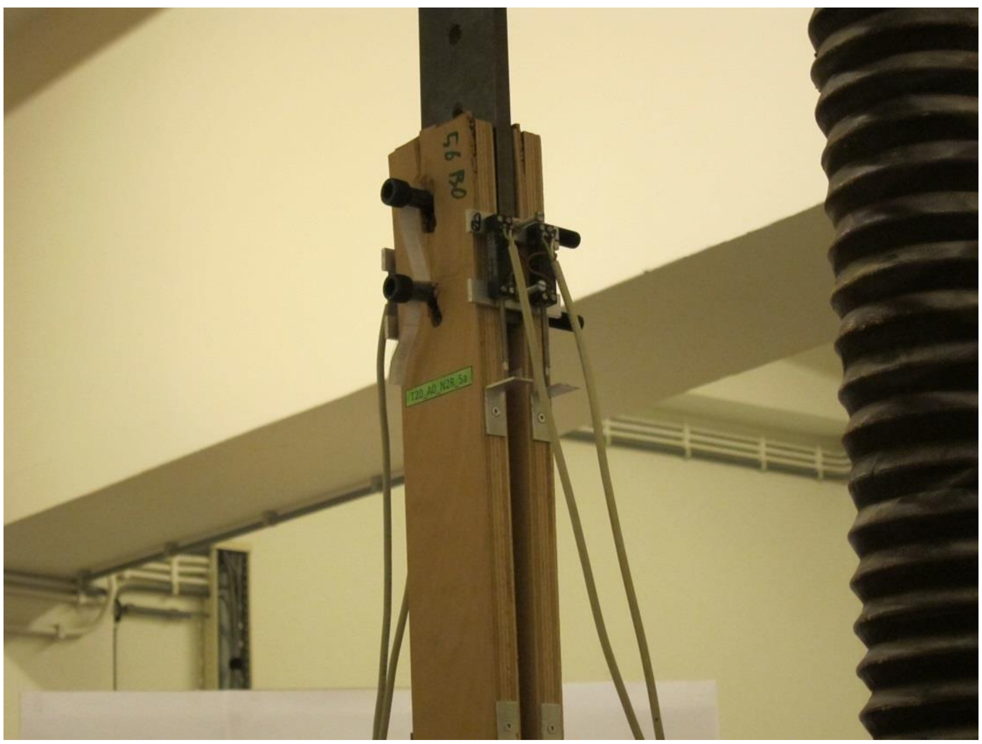


Figure 344 Perspective view nr2. After testing

Data:

T20_A0_N2R_5	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	99,50	10,90	1,78	15,40	13,70
$F_{0,5}$	94,99	5,00	1,63	9,25	10,28
$F_{failure}$	49,62	15,61	1,46	18,59	15,48

Table 106 Results of specimen T20_A0_N2R_5

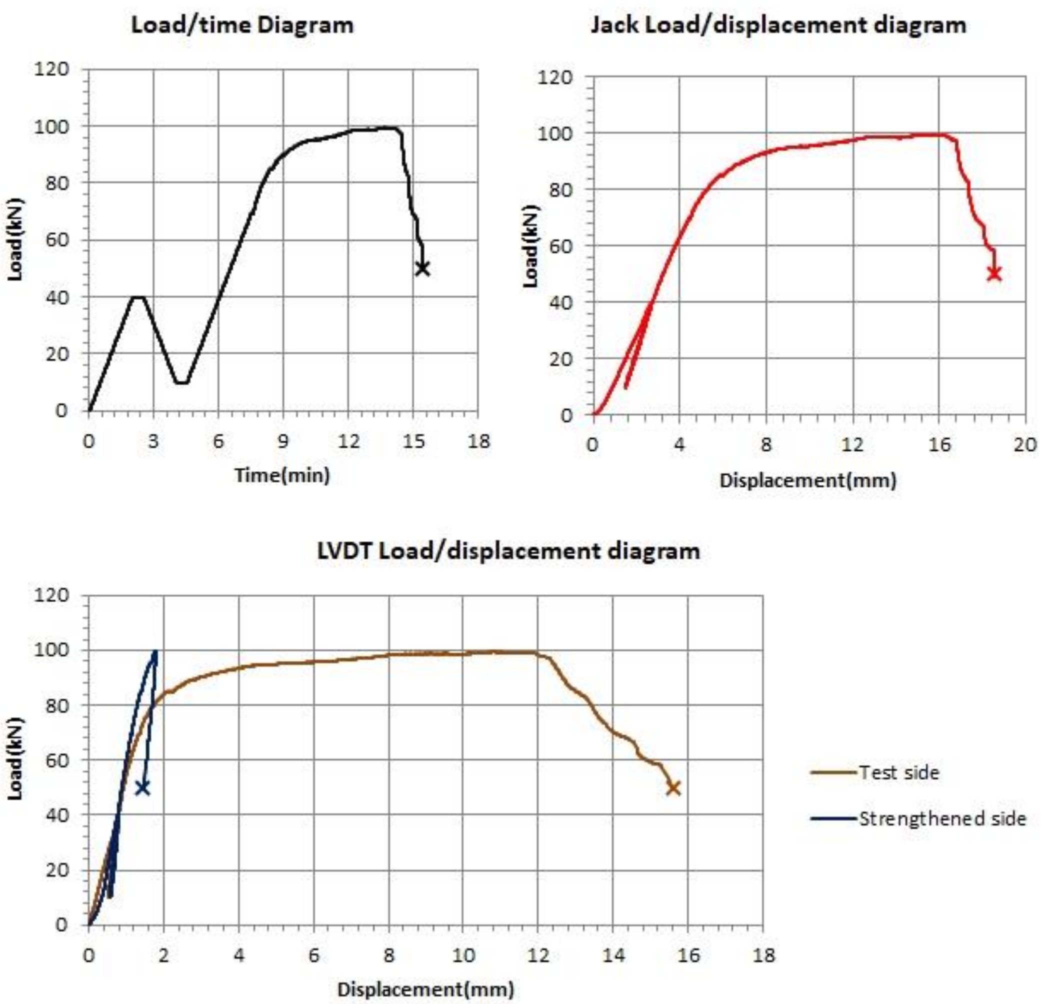


Figure 345 Graphical results of T20_A0_N2R_5

13.8 T20_A0_N3

***Before Testing**(pictures test specimen T20_A0_N3_2 tensile failure):*

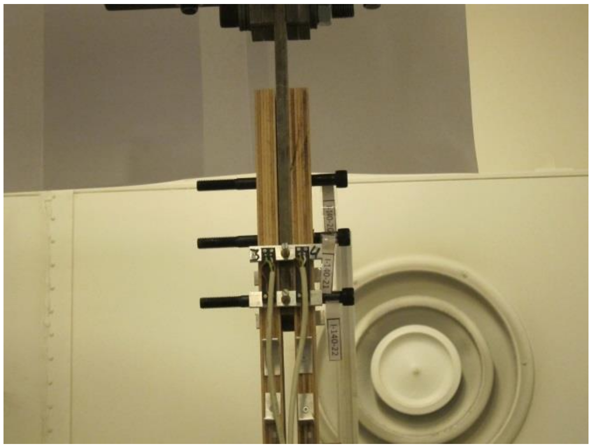


Figure 346 Front view

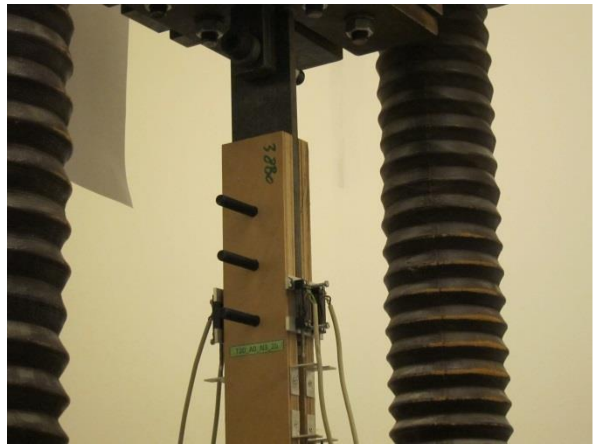


Figure 347 Perspective view nr. 1

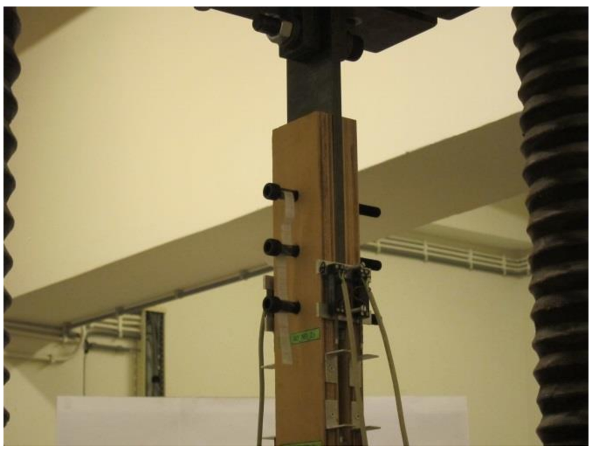


Figure 348 Perspective view nr 2

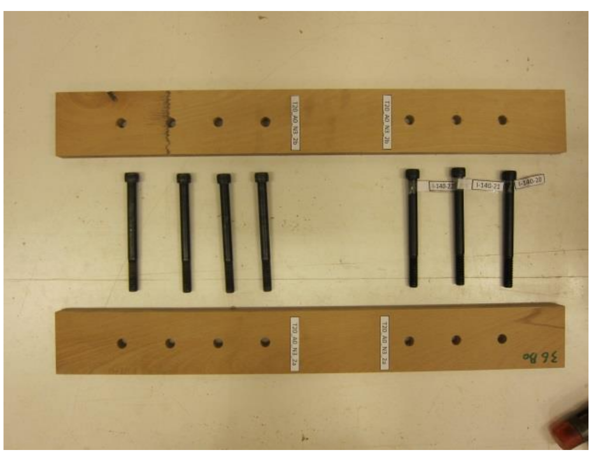


Figure 349 Overview materials

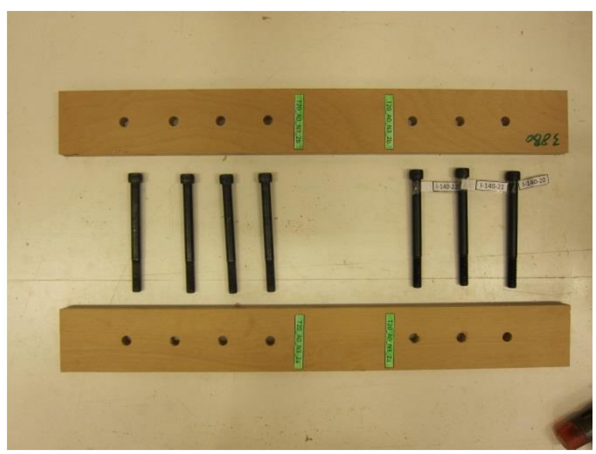


Figure 350 Overview materials

After testing

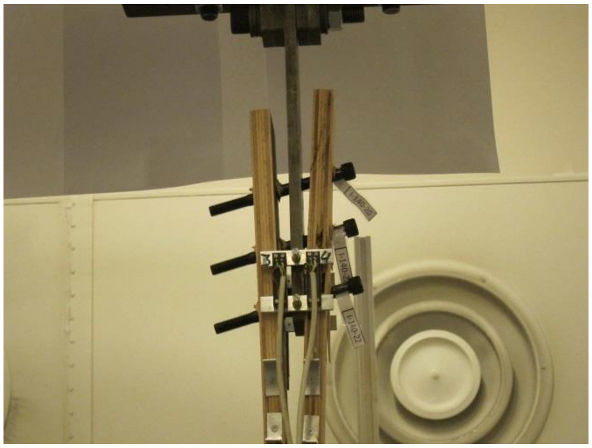


Figure 351 Front view

Figure 352 Perspective view nr. 1

Figure 353 perspective view nr 2

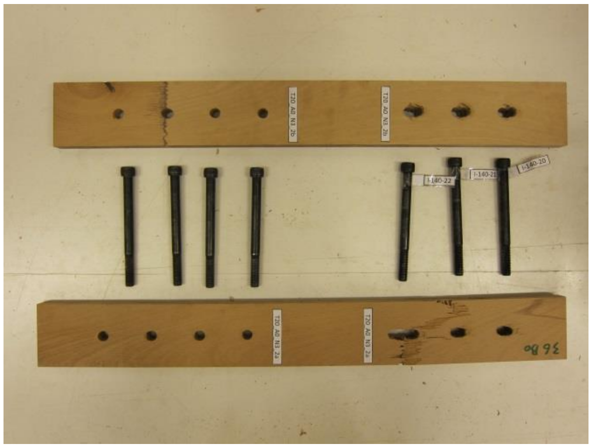


Figure 354 Overview materials

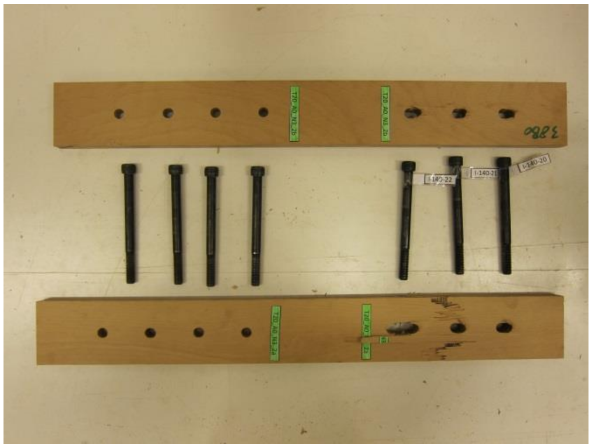


Figure 355 Overview materials

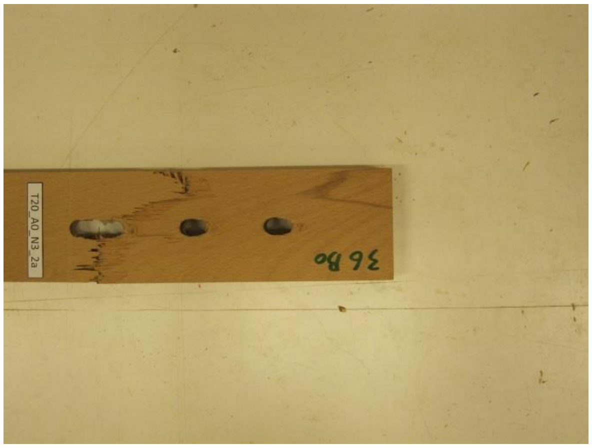


Figure 356 Closeup failure(Surface towards steel plate)

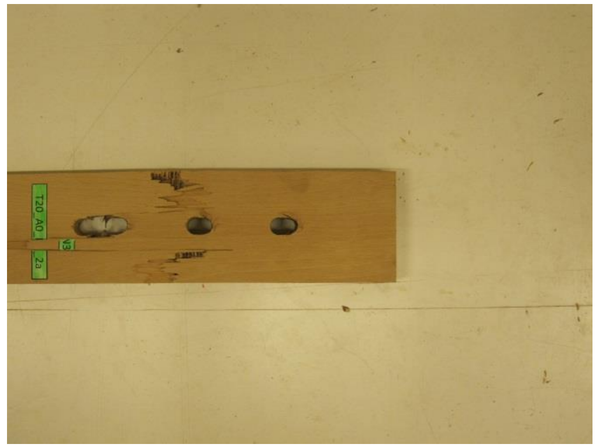


Figure 358 Closeup failure(Surface on the outside)

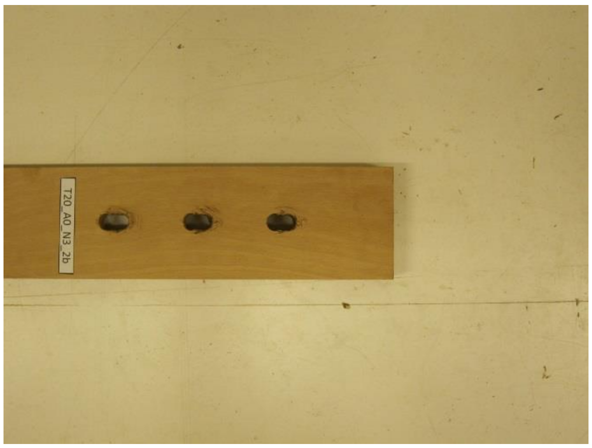


Figure 357 Closeup failure(Surface towards steel plate)

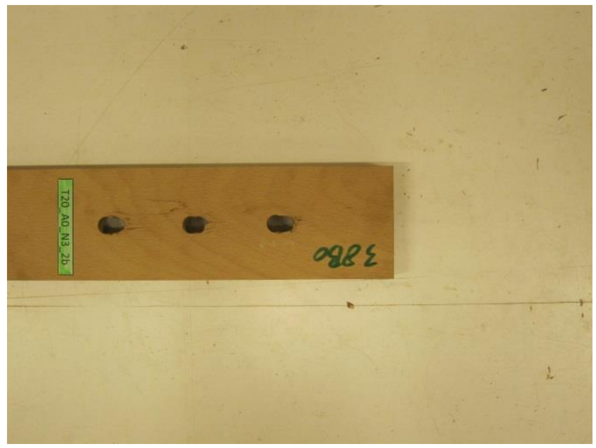


Figure 359 Closeup failure(Surface on the outside)

Figure 360 Dowels after testing strengthened side

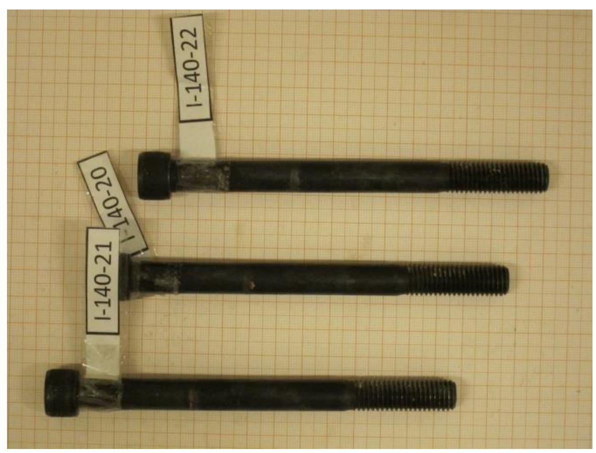


Figure 361 dowels after testing test side

13.8.1 T20_A0_N3_1

Material coding:

Labels Timber	T20_A0_N3_1a	T20_A0_N3_1b		
Labels Steel Test side	I-140-17	I-140-18	I-140-19	
Labels Steel Strengthened. side	Reused	Reused	Reused	Reused

Table 107 Material coding T20_A0_N3_1

Log:

<u>Material</u>: *few cracks located in specimen a strengthened side and a void through cross layer specimen b*
<u>F_{est}:</u> *100kN*
<u>Displacement controlled speed(1):</u> *0.015mm/s*
<u>Displacement controlled speed(2):</u> *0.03mm/s*

<u>During testing</u>: *as planned*

<u>Cause of failure:</u> *embedment/shear*

<u>Additional remarks:</u>

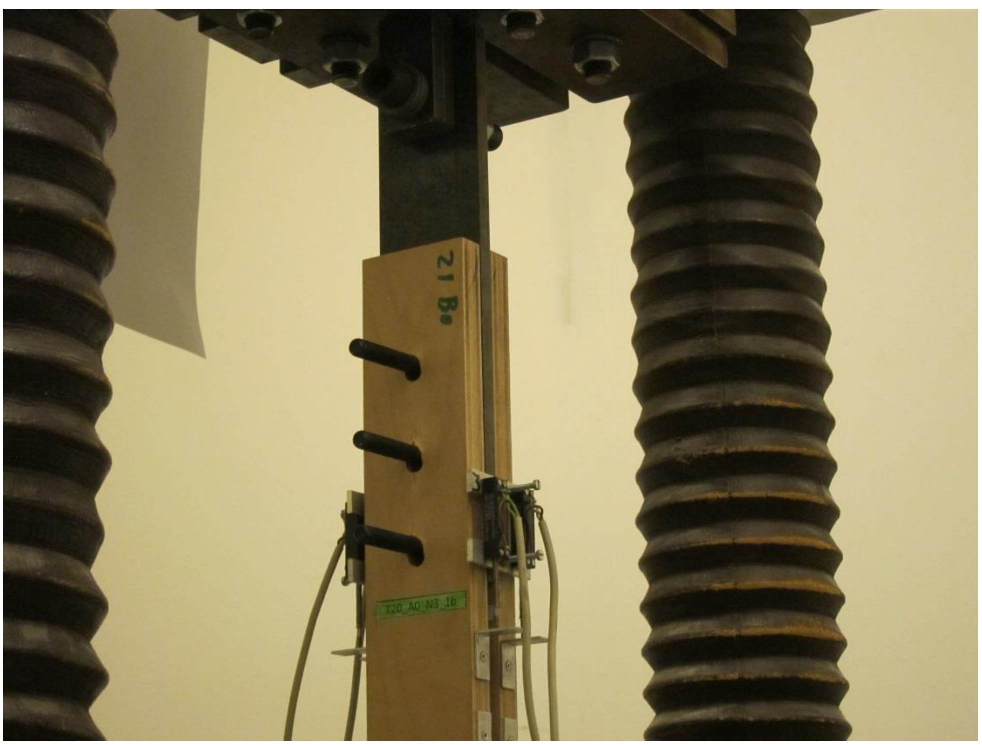
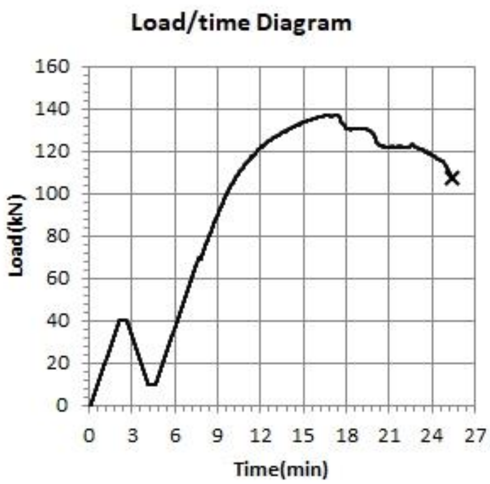


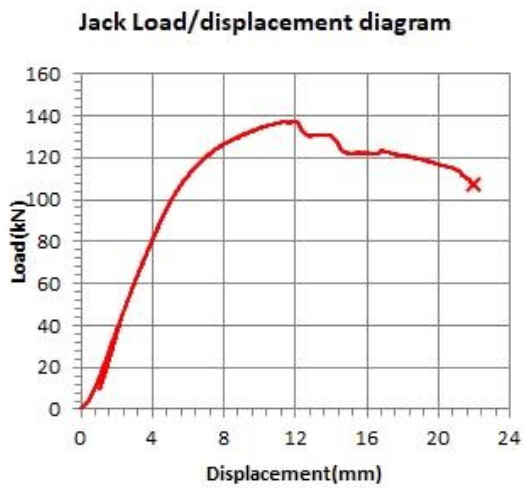
Figure 362 Perspective view nr1. After testing

Data:

T20_A0_N3_1	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	137,45	5,99	2,24	11,47	16,76
$F_{0,5}$	134,90	5,00	2,12	10,31	15,47
$F_{failure}$	106,71	17,09	2,36	22,05	25,48

Table 108 Results of specimen T20_A0_N3_1





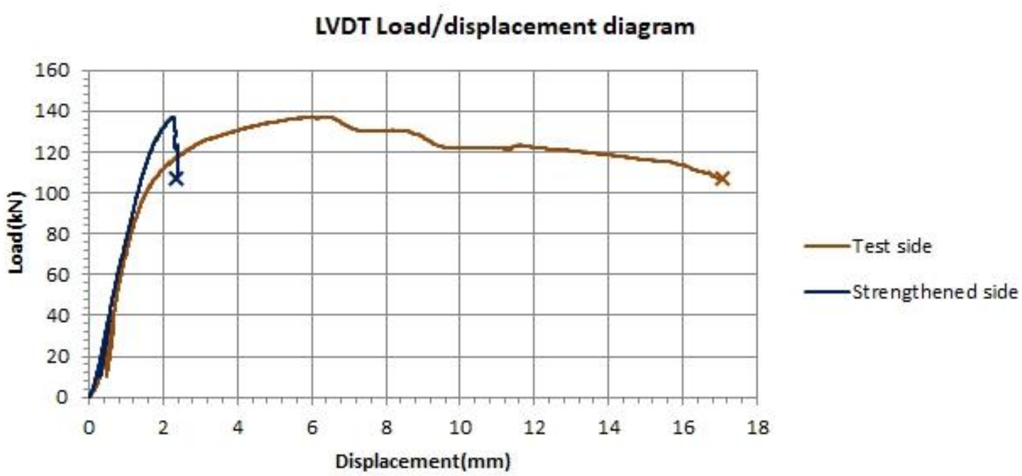


Figure 363 Graphical results of T20_A0_N3_1

13.8.2 T20_A0_N3_2

Material coding:

Labels Timber	T20_A0_N3_2a	T20_A0_N3_2b		
Labels Steel Test side	I-140-20	I-140-21	I-140-22	
Labels Steel Strengthened. side	Reused	Reused	Reused	Reused

Table 109 Material coding T20_A0_N3_2

Log:

Material: *seam in specimen b no further noticable imperfections*
F_{est}: *135kN*
Displacement controlled speed(1): *0.025mm/s*
Displacement controlled speed(2): *-mm/s*

During testing: *as planned*

Cause of failure: *tensile failure*

Additional remarks:

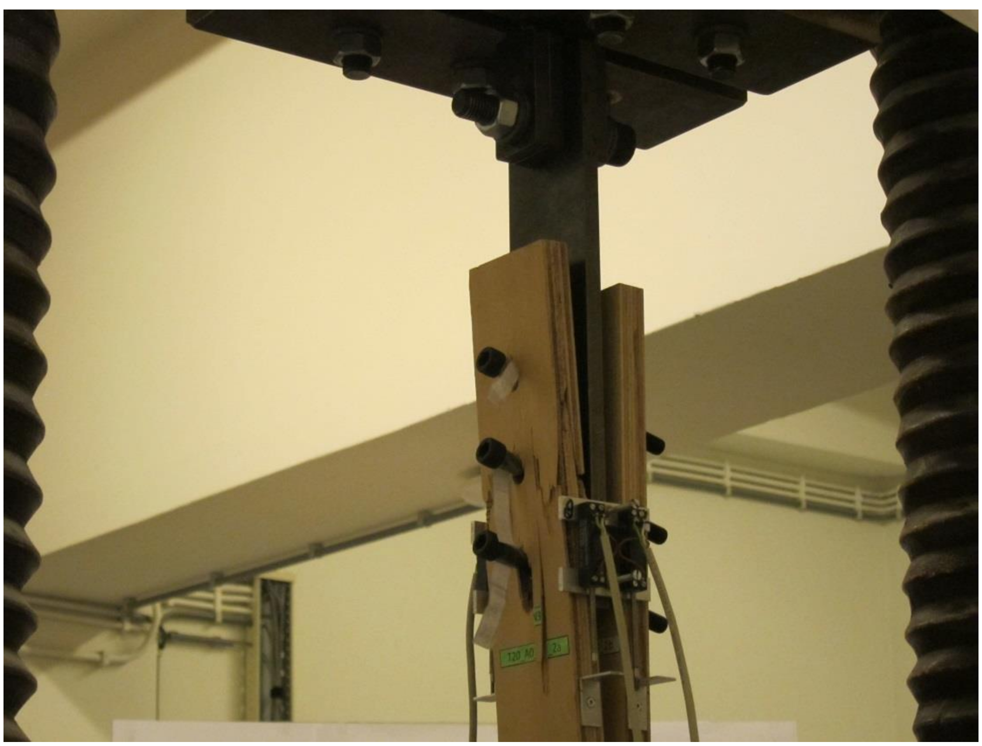


Figure 364 Perspective view nr2. After testing

Data:

T20_A0_N3_2	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	142,18	9,82	3,07	16,56	14,61
$F_{0,5}$	133,41	5,00	2,78	11,18	11,02
$F_{failure}$	140,85	9,87	3,07	16,59	14,62

Table 110 Results of specimen T20_A0_N3_2

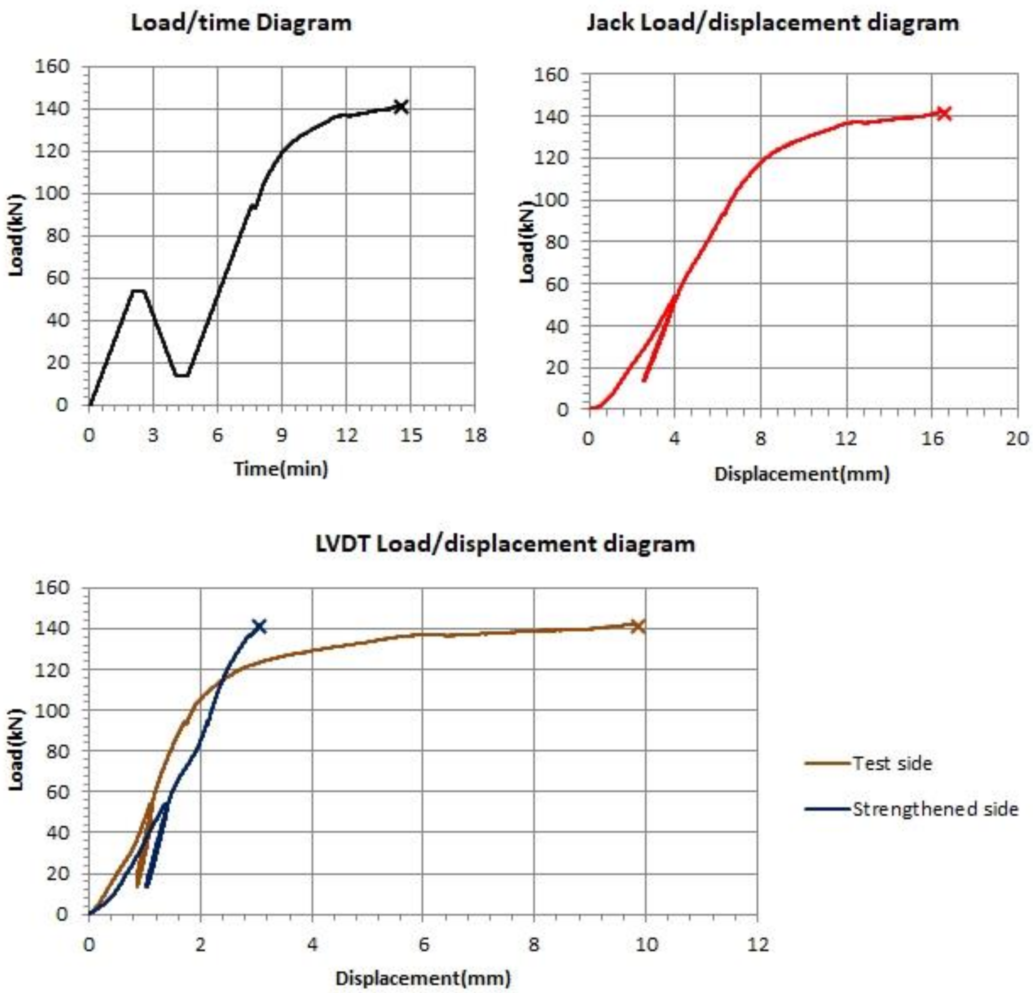


Figure 365 Graphical results of T20_A0_N3_2

13.8.3 T20_A0_N3_3

Material coding:

Labels Timber	T20_A0_N3_3a	T20_A0_N3_3b		
Labels Steel Test side	I-140-23	I-140-24	I-140-25	
Labels Steel Strengthened. side	Reused	Reused	Reused	Reused

Table 111 Material coding T20_A0_N3_3

Log:

Material: *small void in cross veneer specimen a*

F_{est}: *135kN*
Displacement controlled speed(1): *0.025mm/s*
Displacement controlled speed(2): *mm/s*

During testing: *as planned*

Cause of failure: *tensile failure*

Additional remarks:

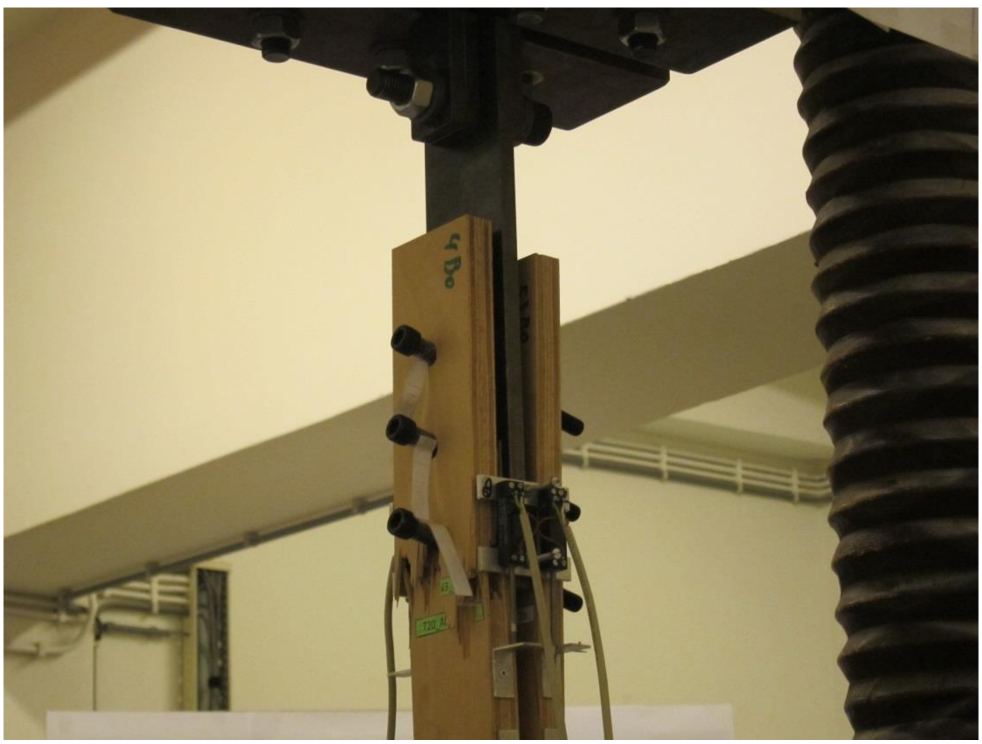


Figure 366 Perspective view nr2. After testing

Data:

T20_A0_N3_3	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	135,05	4,25	1,91	9,26	10,66
$F_{0,5}$	-	-	-	-	-
$F_{failure}$	134,76	4,30	1,90	9,28	10,68

Table 112 Results of specimen T20_A0_N3_3

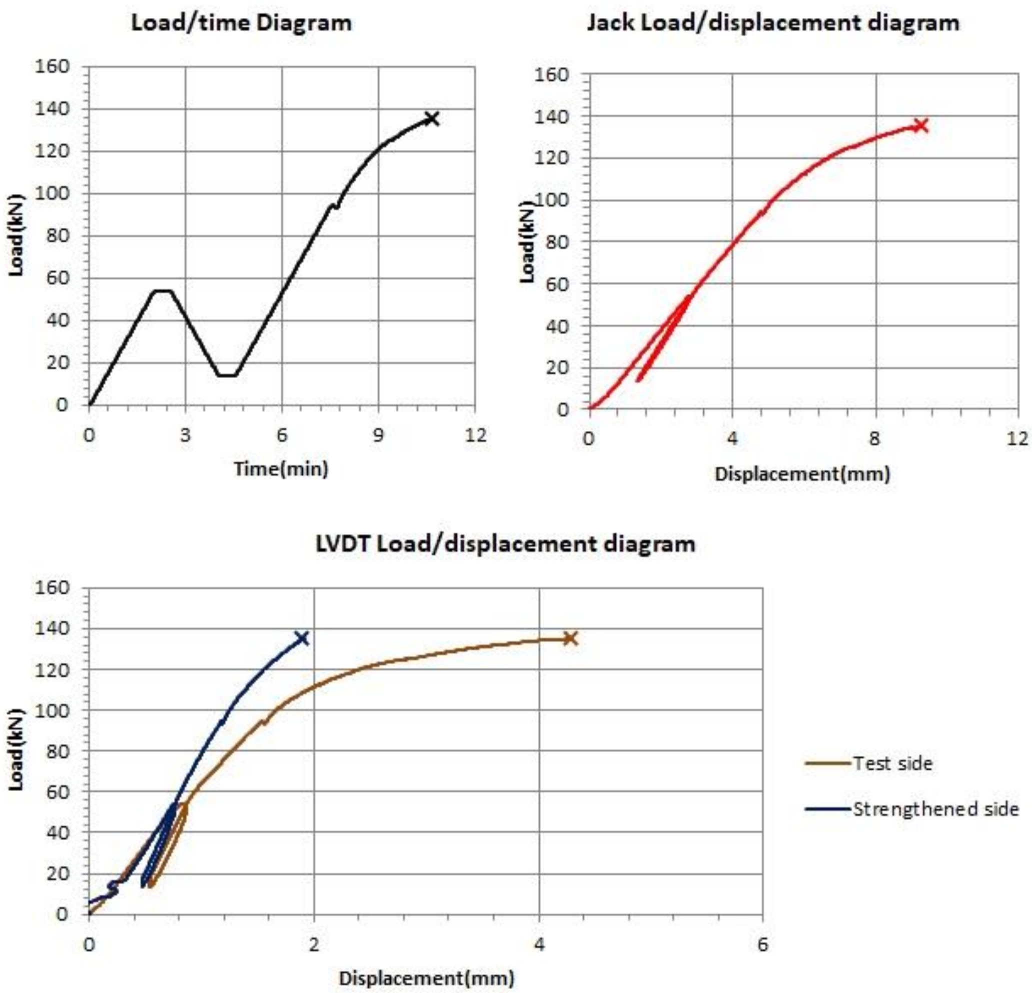


Figure 367 Graphical results of T20_A0_N3_3

13.8.4 T20_A0_N3_4

Material coding:

Labels Timber	T20_A0_N3_4a	T20_A0_N3_4b		
Labels Steel Test side	I-140-26	I-140-27	I-140-28	
Labels Steel Strengthened. side	Reused	Reused	Reused	Reused

Table 113 Material coding T20_A0_N3_4

Log:

Material: *Top veneer specimen b damaged at the end and veneer seam in specimen a.*
F_{est}: *135kN*
Displacement controlled speed(1): *mm/s*
Displacement controlled speed(2): *mm/s*

During testing: *as planned*

Cause of failure: *tensile failure*

Additional remarks:

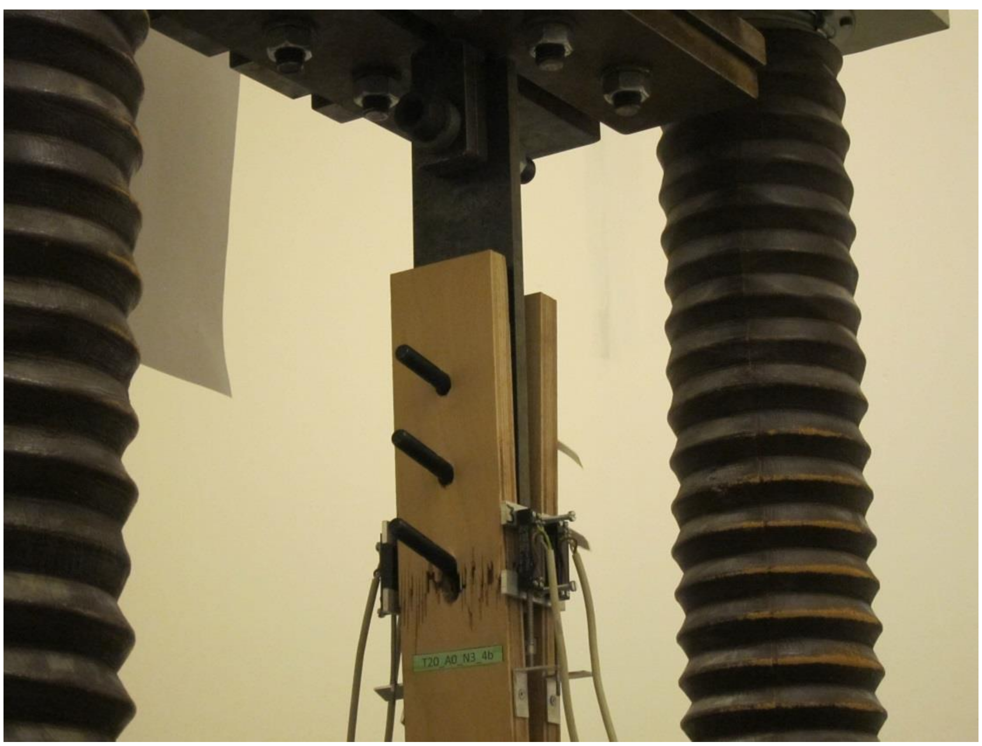


Figure 368 Perspective view nr1. After testing

Data:

T20_A0_N3_4	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	135,00	3,97	1,81	9,06	10,59
$F_{0,5}$	-	-	-	-	-
$F_{failure}$	133,43	4,17	1,82	9,23	10,70

Table 114 Results of specimen T20_A0_N3_4

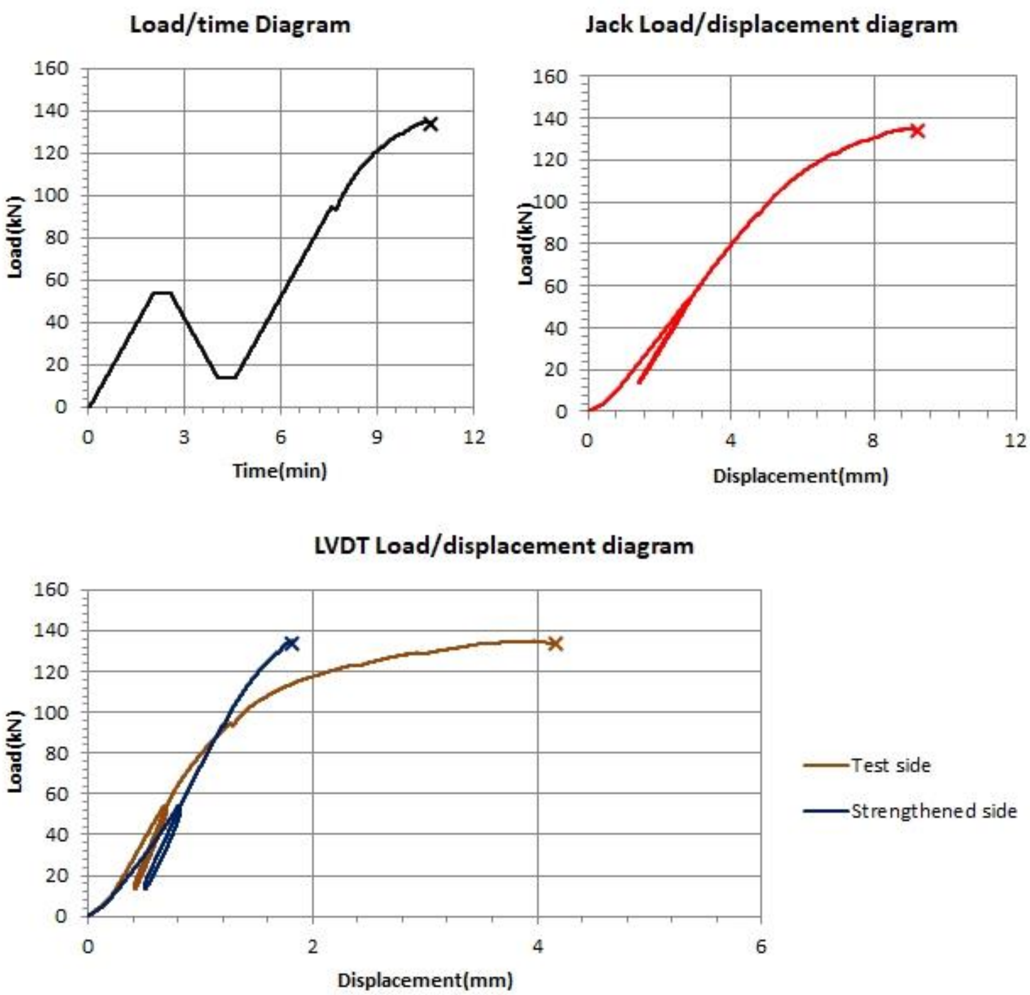


Figure 369 Graphical results of T20_A0_N3_4

13.8.5 T20_A0_N3_5

Material coding:

Labels Timber	T20_A0_N3_4a	T20_A0_N3_4b		
Labels Steel Test side	I-140-29	I-140-30	I-140-31	
Labels Steel Strengthened. side	Reused	Reused	Reused	Reused

Table 115 Material coding T20_A0_N3_5

Log:

Material: *Veneer seam in specimen b, overall clear specimen*
F_{est}: *135kN*
Displacement controlled speed(1): *0.025mm/s*
Displacement controlled speed(2): *mm/s*

During testing: *as planned*

Cause of failure: *tensile failure*

Additional remarks:

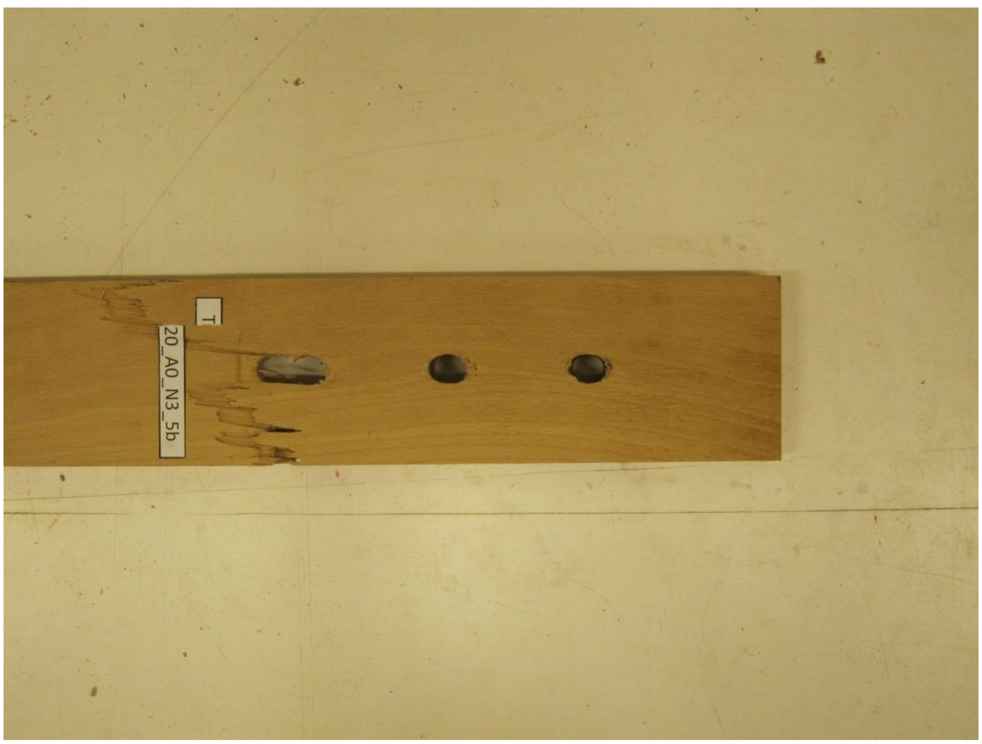


Figure 370 closeup test specimen(after perspective views are missing)

Data:

T20_A0_N3_5	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	139,15	4,29	2,38	9,88	10,74
$F_{0,5}$	-	-	-	-	-
$F_{failure}$	139,15	4,29	2,38	9,88	10,74

Table 116 Results of specimen T20_A0_N3_5

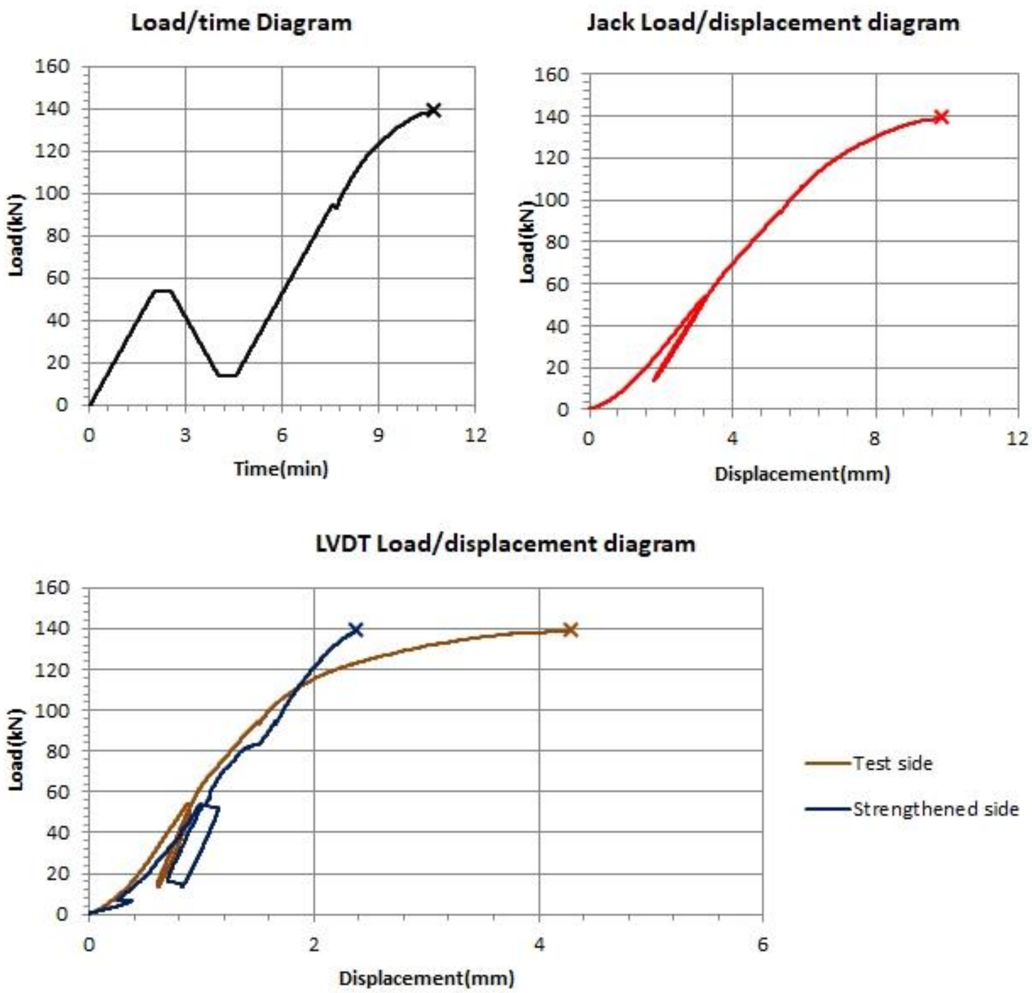


Figure 371 Graphical results of T20_A0_N3_5

13.9 T20_A0_N3R_S

<u>Before Testing</u>(pictures test specimen T20_A0_N3R_2 tensile failure)<u>:</u>

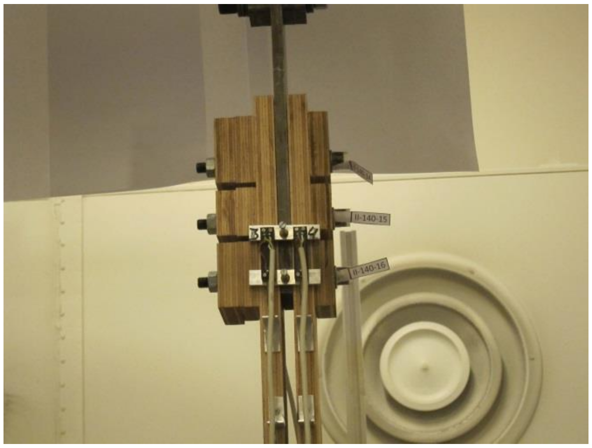


Figure 372 Front view

Figure 373 Perspective view nr. 1

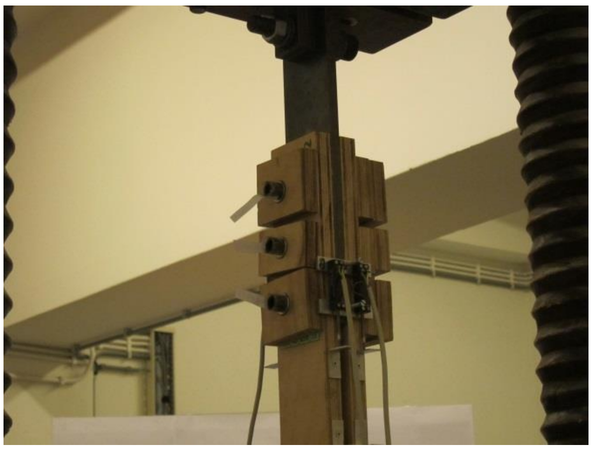


Figure 374 Perspective view nr 2

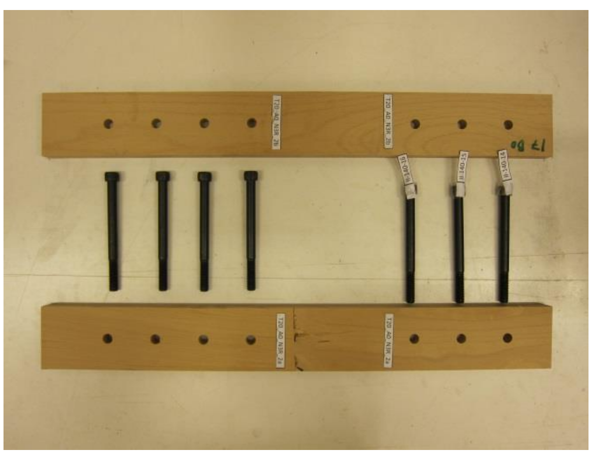


Figure 375 Overview materials

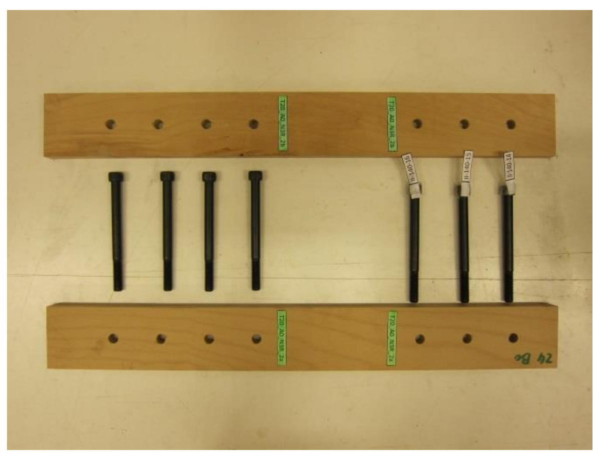


Figure 376 Overview materials

After testing

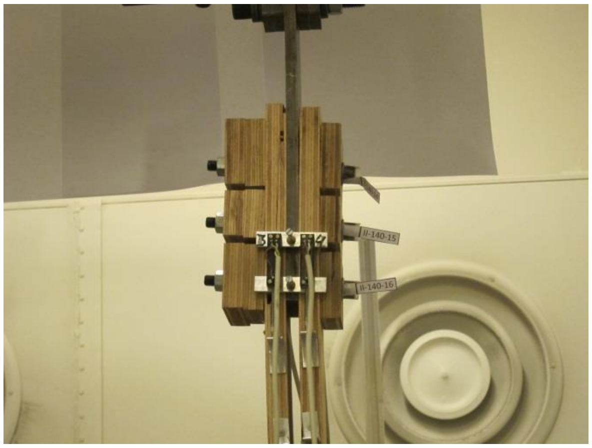


Figure 377 Front view

Figure 378 Perspective view nr. 1

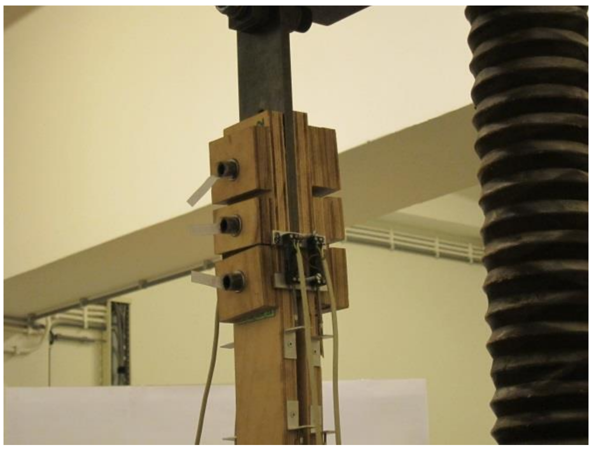


Figure 379 perspective view nr 2

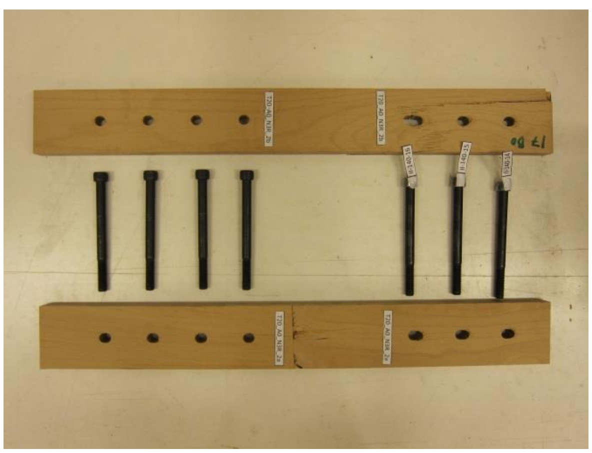


Figure 380 Overview materials

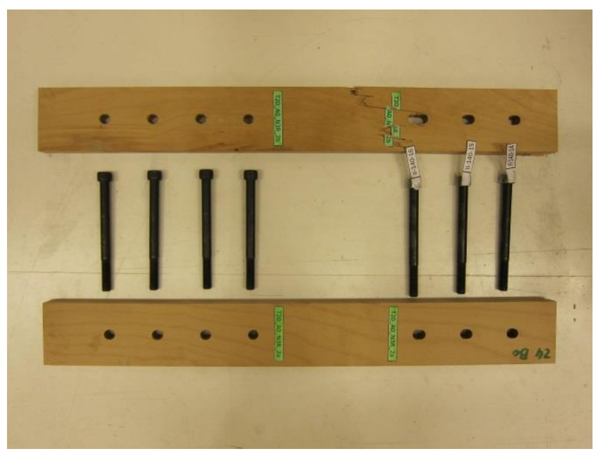


Figure 381 Overview materials

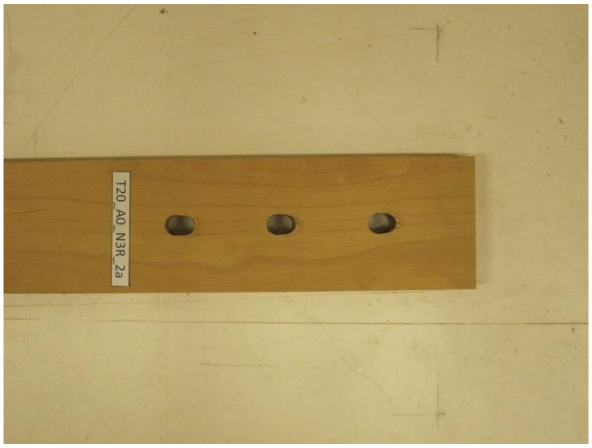


Figure 382 Closeup failure(Surface towards steel plate)

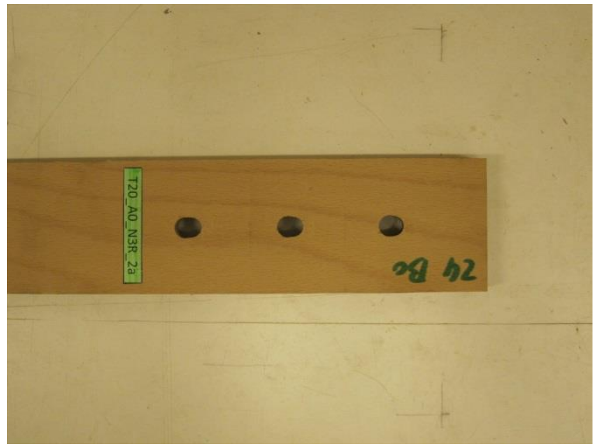


Figure 384 Closeup failure(Surface on the outside)

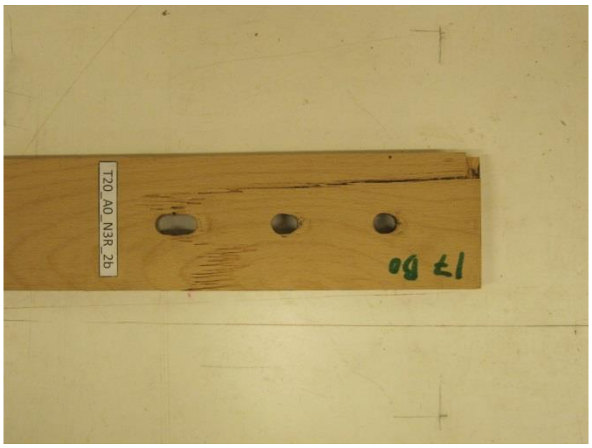


Figure 383 Closeup failure(Surface towards steel plate)

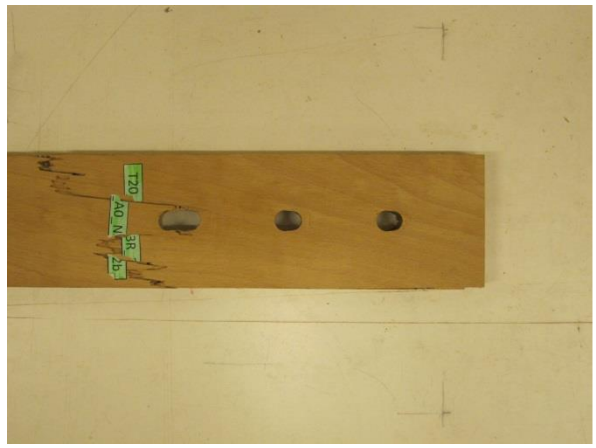


Figure 385 Closeup failure(Surface on the outside)

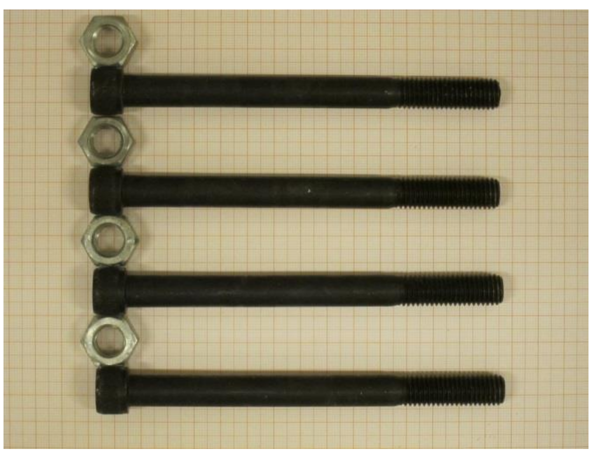


Figure 386 Dowels after testing strengthened side

Figure 387 dowels after testing test side

13.9.1 T20_A0_N3R_1S

Material coding:

Labels Timber	T20_A0_N3R_1a	T20_A0_N3R_1b		
Labels Steel Test side	II-140_11	II-140_12	II-140_13	
Labels Steel Strengthened. side	new	new	new	new

Table 117 Material coding T20_A0_N3R_1S

Log:

Material: *clear specimen*

F_{est}: *135kN*
Displacement controlled speed(1): *0.025mm/s*
Displacement controlled speed(2): *-mm/s*

During testing: *as planned*

Cause of failure: *tensile failure*

Additional remarks:

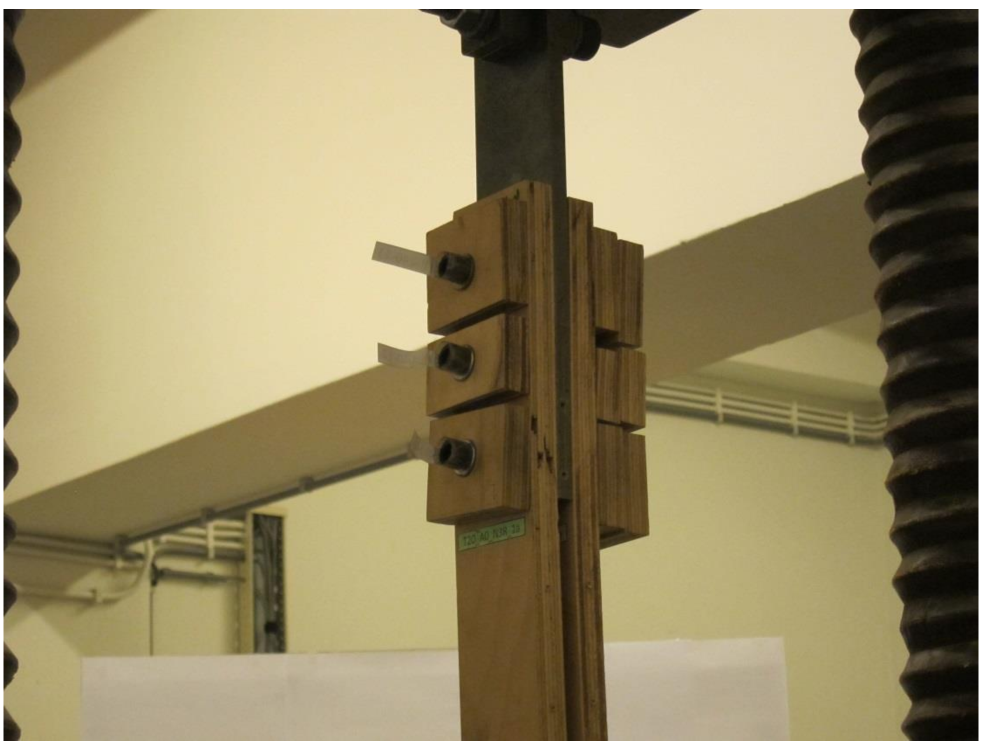
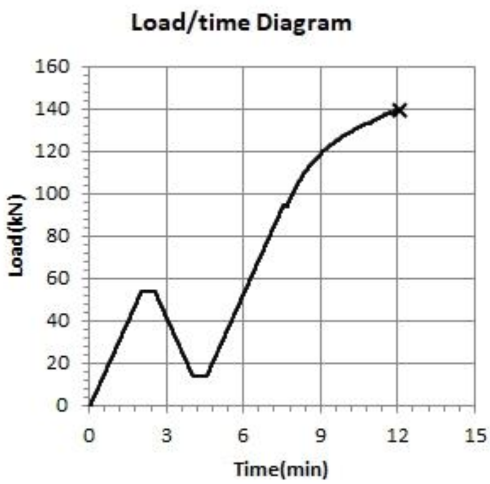


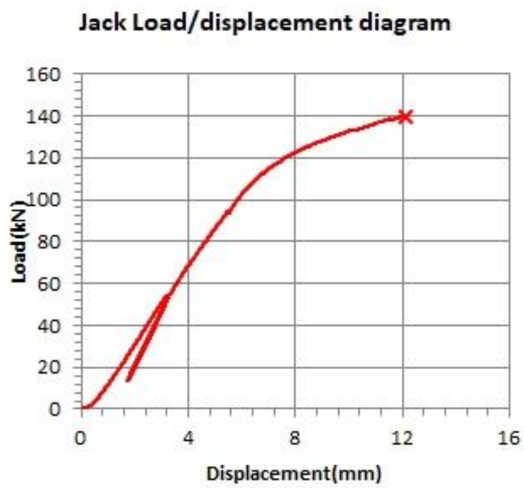
Figure 388 Perspective view nr2. After testing

Data:

T20_A0_N3R_1S	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	139,53	6,00	2,57	12,01	12,02
$F_{0,5}$	135,01	5,00	2,39	10,73	11,17
$F_{failure}$	139,26	6,11	2,58	12,13	12,10

Table 118 Results of specimen T20_A0_N3R_1S





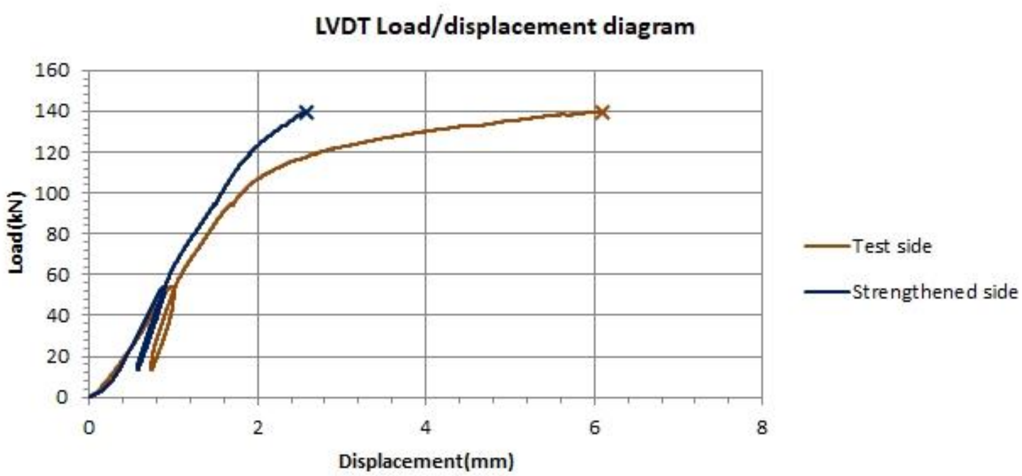


Figure 389 Graphical results of T20_A0_N3R_1S

13.9.2 T20_A0_N3R_2S

Material coding:

Labels Timber	T20_A0_N3R_2a	T20_A0_N3R_2b		
Labels Steel Test side	II-140-14	II-140-15	II-140-16	
Labels Steel Strengthened. side	new	new	new	new

Table 119 Material coding T20_A0_N3R_2S

Log:

Material: *seam and small void in specimen a. Specimen b had a very thin top veneer*
F_{est}: *135kN*
Displacement controlled speed(1): *0.025mm/s*
Displacement controlled speed(2): *mm/s*

During testing: *as planned*

Cause of failure: *tensile failure*

Additional remarks:

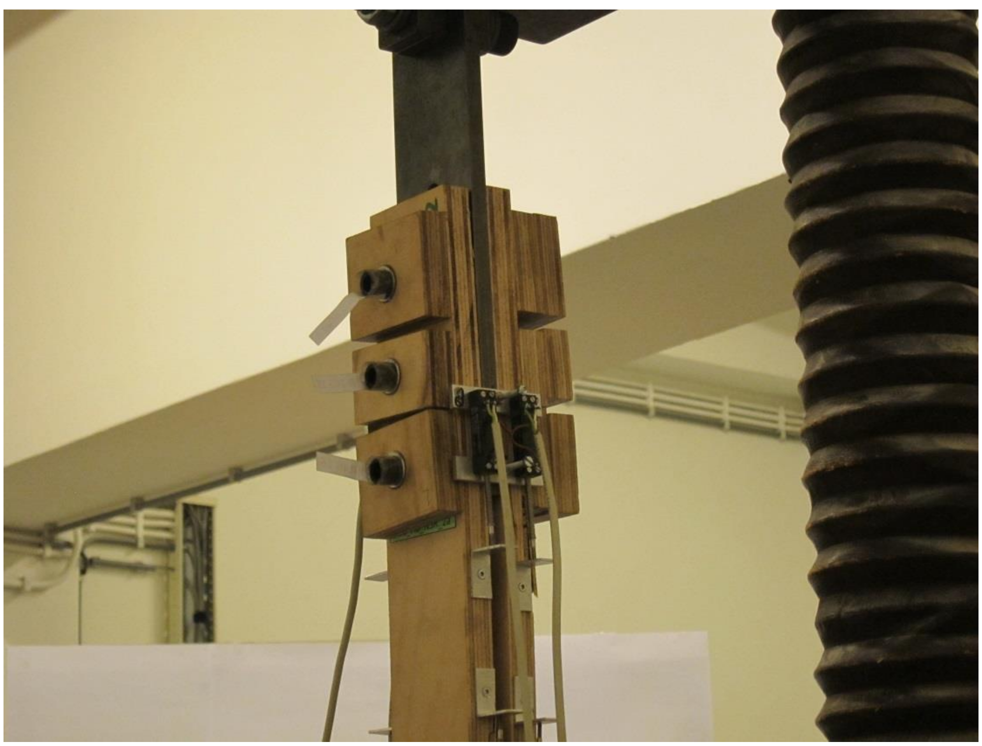
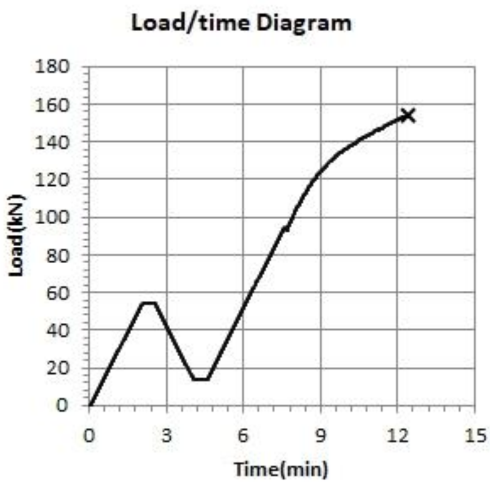


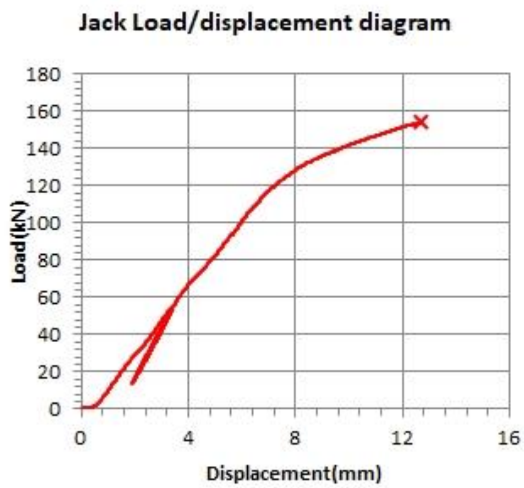
Figure 390 Perspective view nr2. After testing

Data:

T20_A0_N3R_2S	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	153,97	6,40	2,70	12,73	12,43
$F_{0,5}$	146,01	5,00	2,38	10,80	11,14
$F_{failure}$	153,83	6,41	2,70	12,74	12,43

Table 120 Results of specimen T20_A0_N3R_2S





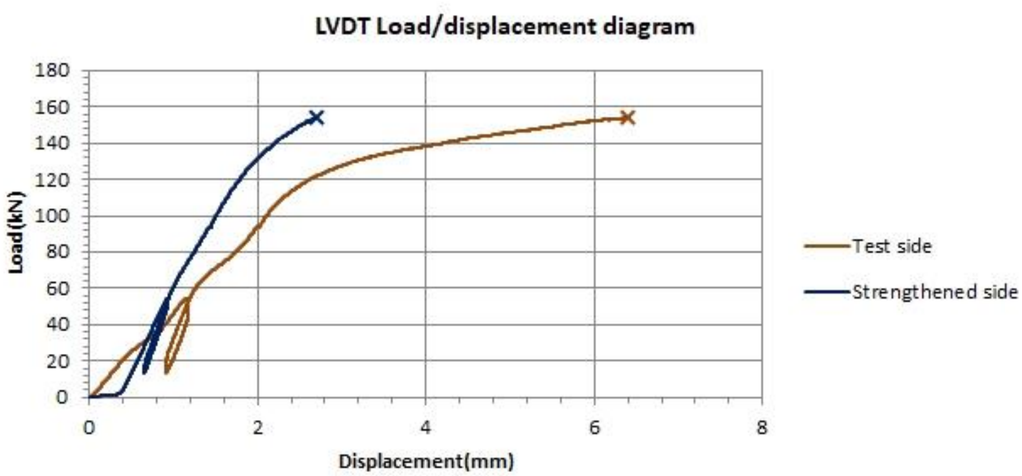


Figure 391 Graphical results of T20_A0_N3R_2S

13.9.3 T20_A0_N3R_3S

Material coding:

Labels Timber	T20_A0_N3R_3a	T20_A0_N3R_3b		
Labels Steel Test side	II-140-17	II-140-18	II-140-19	
Labels Steel Strengthened. side	new	new	new	new

Table 121 Material coding T20_A0_N3R_3S

Log:

Material: *clear specimen*

F_{est}**:** *135kN*
Displacement controlled speed(1): *0.025mm/s*
Displacement controlled speed(2): *-mm/s*

During testing: as planned

Cause of failure: *tensile failure*

Additional remarks:

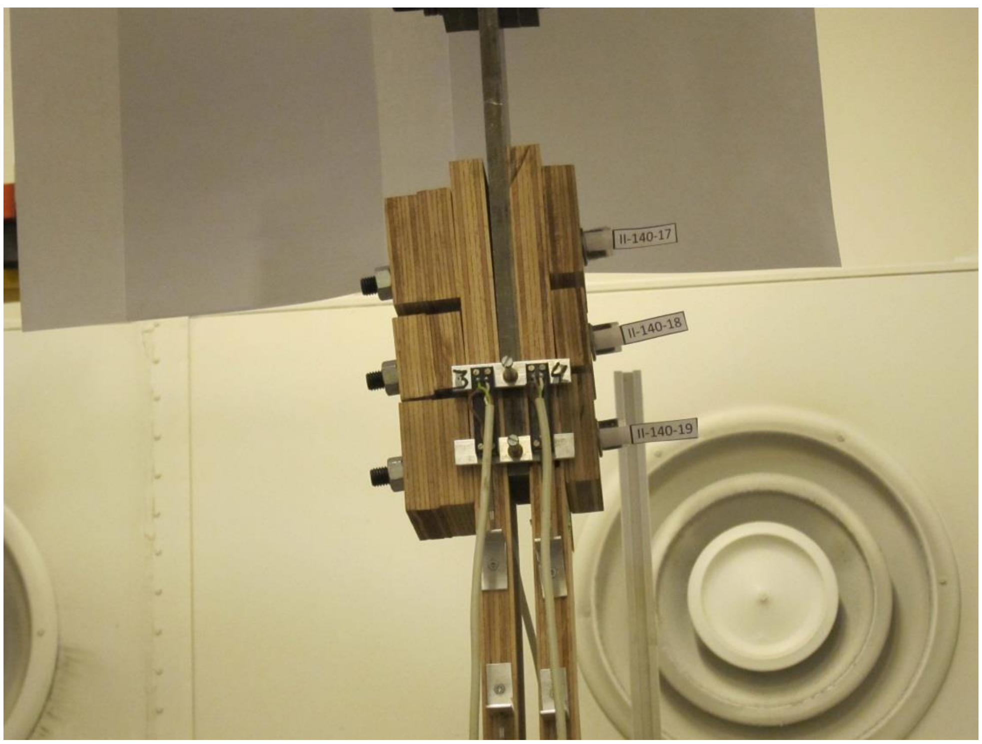


Figure 392 Perspective Front view

Data:

T20_A0_N3R_3S	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	150,25	6,46	2,40	12,42	12,34
$F_{0,5}$	143,88	5,00	2,17	10,59	11,12
$F_{failure}$	148,23	6,62	2,42	12,58	12,44

Table 122 Results of specimen T20_A0_N3R_3S

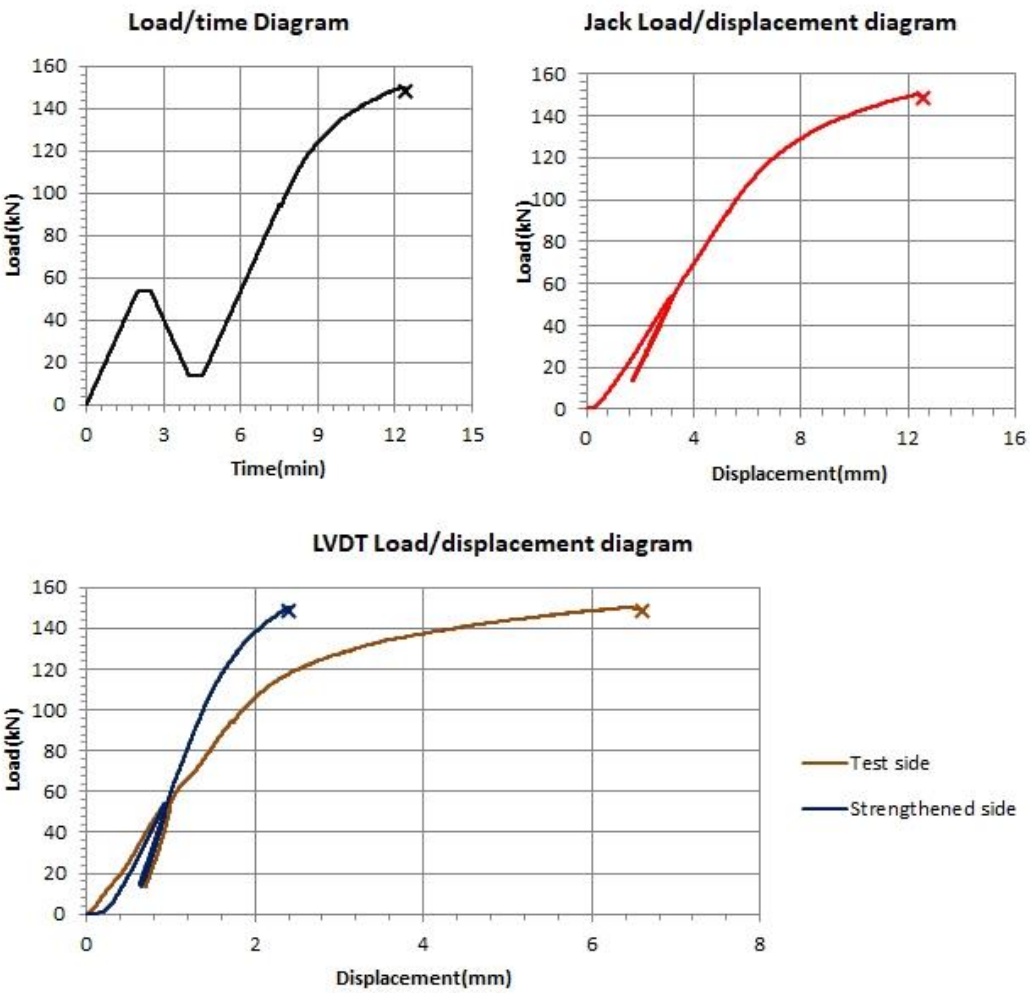


Figure 393 Graphical results of T20_A0_N3R_3S

13.9.4 T20_A0_N3R_4S

Material coding:

Labels Timber	T20_A0_N3R_4a	T20_A0_N3R_4b		
Labels Steel Test side	II-140-22	II-140-23	II-140-24	
Labels Steel Strengthened. side	new	new	new	new

Table 123 Material coding T20_A0_N3R_4S

Log:

Material: *clear specimen*

F$_{est}$: *135kN*
Displacement controlled speed(1): *0.025mm/s*
Displacement controlled speed(2): *-mm/s*

During testing: *as planned*

Cause of failure: *tensile failure*

Additional remarks: *failure occurred at strengthened side instead of test side*

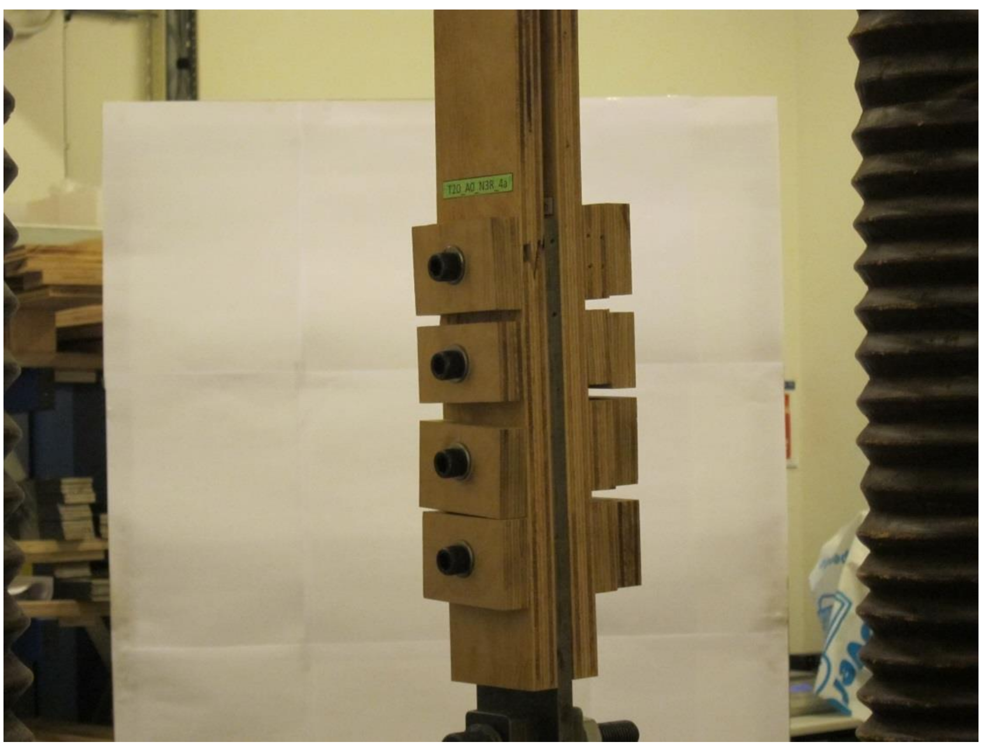


Figure 394 Perspective view nr1. After testing(strengthened side)

Data:

T20_A0_N3R_4S	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	138,41	4,41	2,26	10,23	10,50
$F_{0,5}$	-	-	-	-	-
$F_{failure}$	138,41	4,44	2,27	10,28	10,53

Table 124 Results of specimen T20_A0_N3R_4S

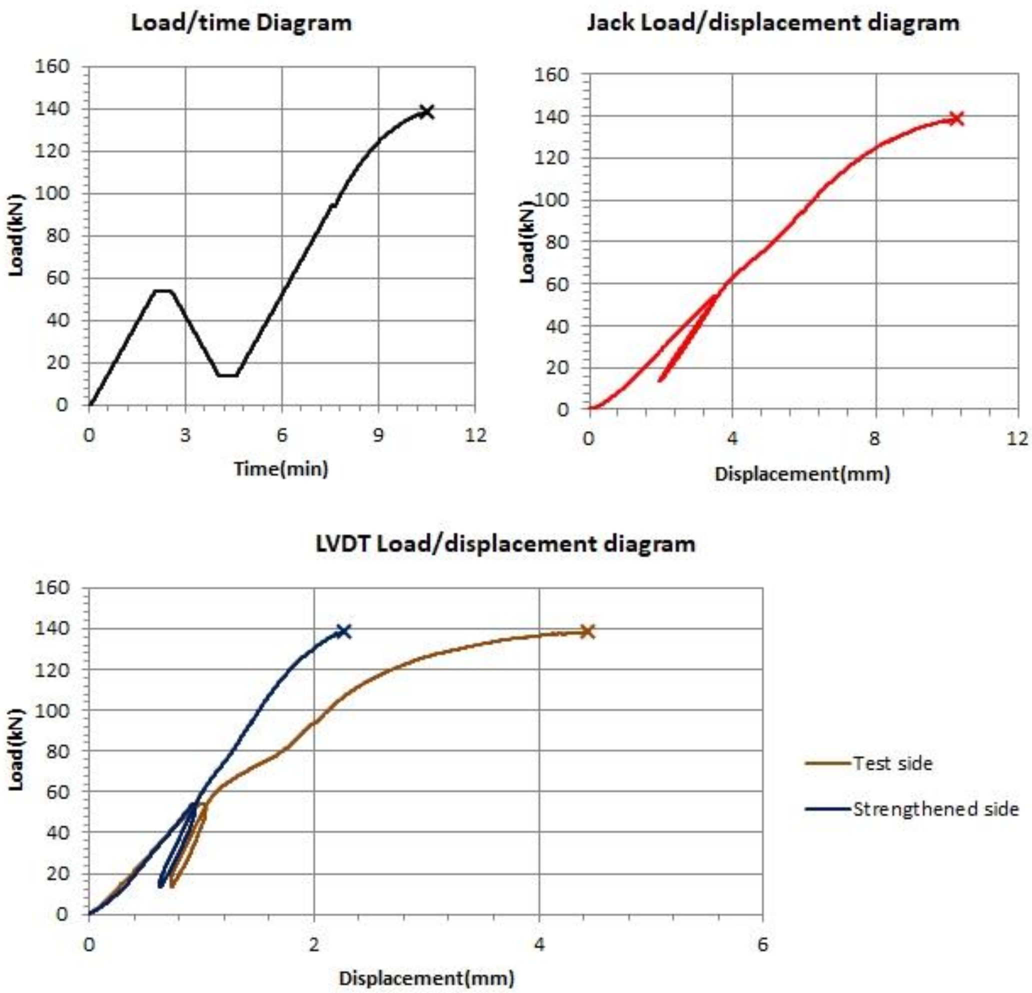


Figure 395 Graphical results of T20_A0_N3R_4S

13.9.5 T20_A0_N3R_5S

Material coding:

Labels Timber	T20_A0_N3R_4a	T20_A0_N3R_4b		
Labels Steel Test side	II-140-25	II-140-26	II-140-27	
Labels Steel Strengthened. side	new	new	new	new

Table 125 Material coding T20_A0_N3R_5S

Log:

<u>Material</u>: *clear specimen*

<u>F_{est}:</u> *135kN*
<u>Displacement controlled speed(1):</u> *0.025mm/s*
<u>Displacement controlled speed(2):</u> *-mm/s*

<u>During testing</u>: *as planned*

<u>Cause of failure:</u> *tensile failure*

<u>Additional remarks:</u>

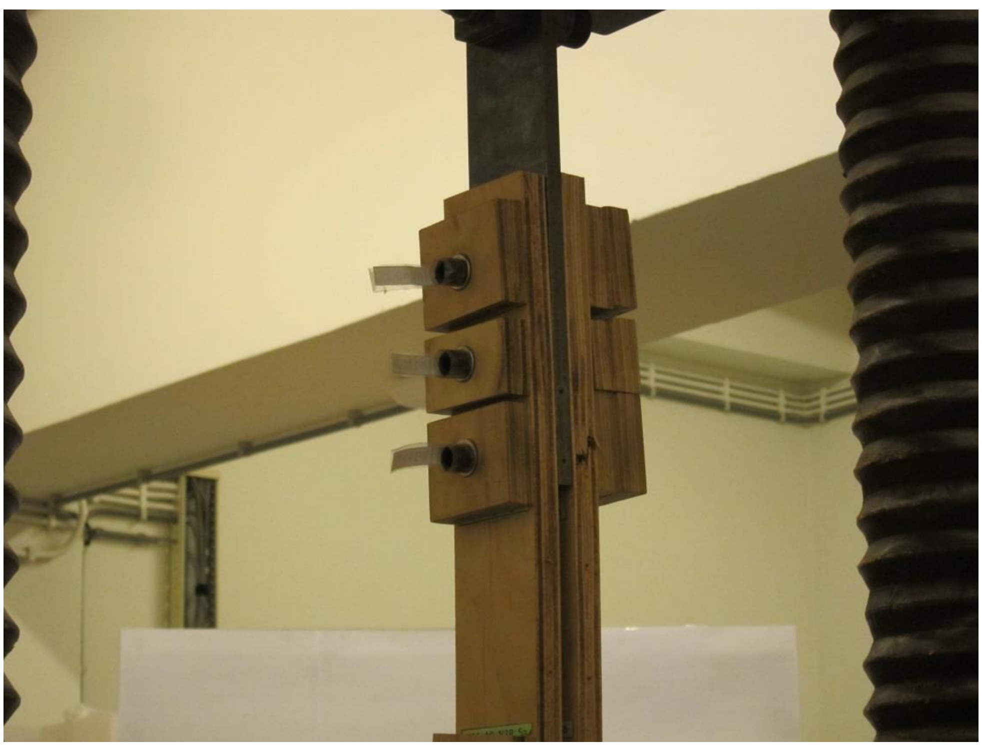


Figure 396 Perspective view nr2. After testing

Data:

T20_A0_N3R_5S	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	113,04	2,08	1,58	6,34	8,37
$F_{0,5}$	-	-	-	-	-
$F_{failure}$	112,25	2,12	1,58	6,36	8,39

Table 126 Results of specimen T20_A0_N3R_5S

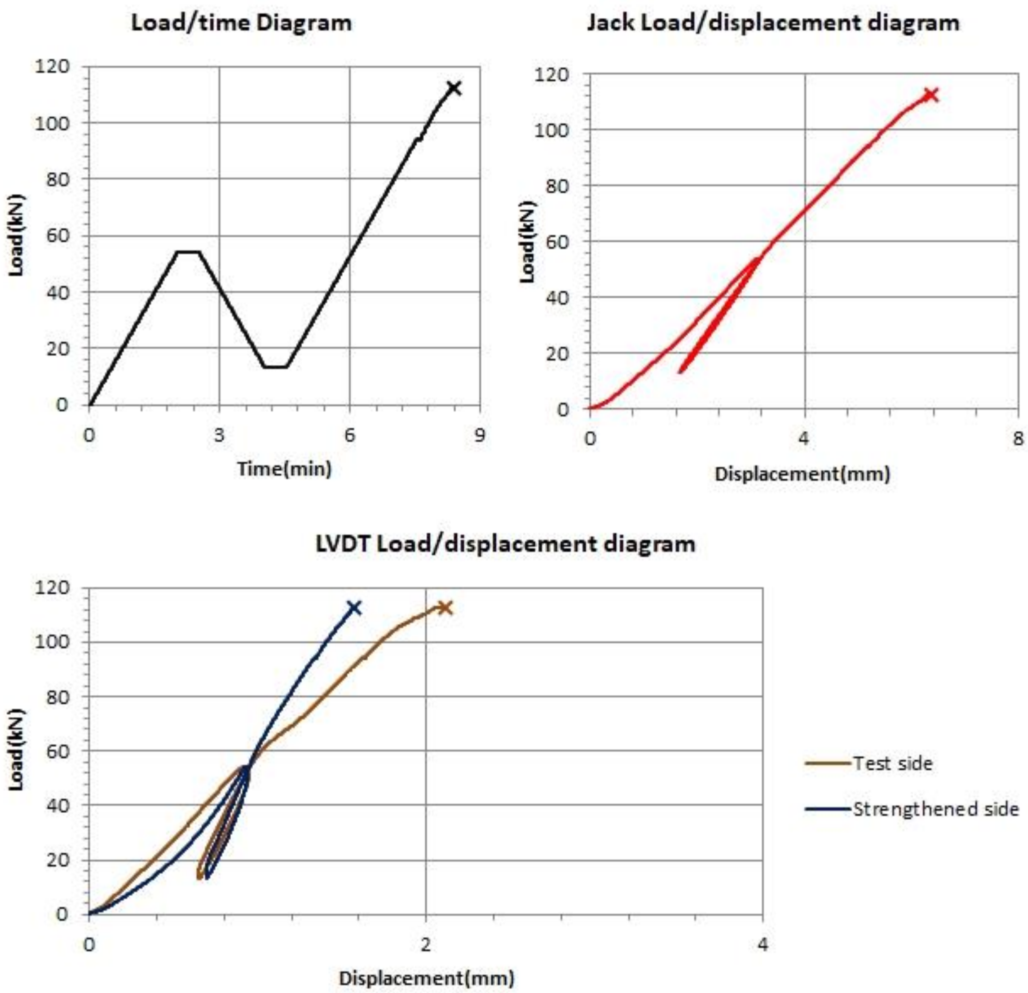


Figure 397 Graphical results of T20_A0_N3R_5S

13.10 T20_A45_N1

<u>Before Testing</u>(pictures test specimen T20_A45_N1_2 embedment failure):

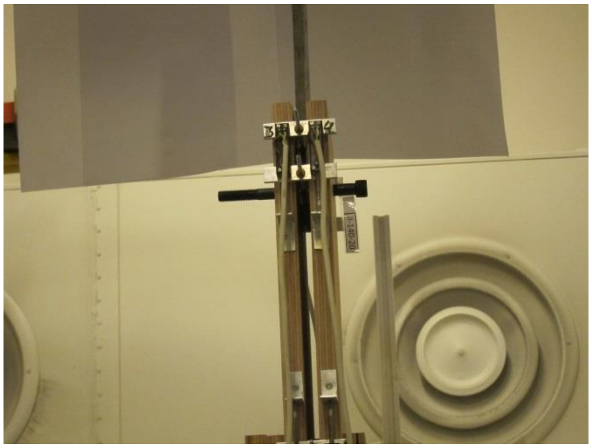


Figure 398 Front view

Figure 399 Perspective view nr. 1

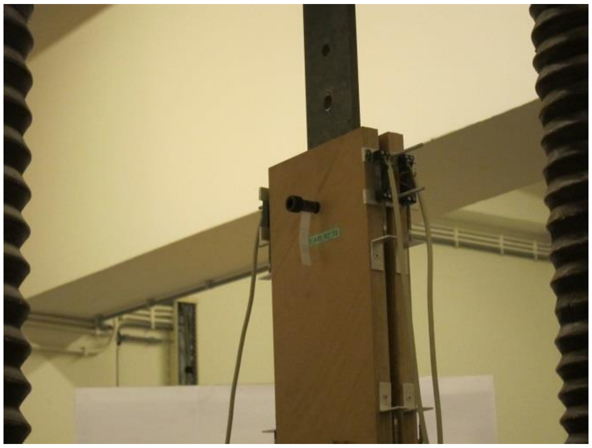


Figure 400 Perspective view nr 2

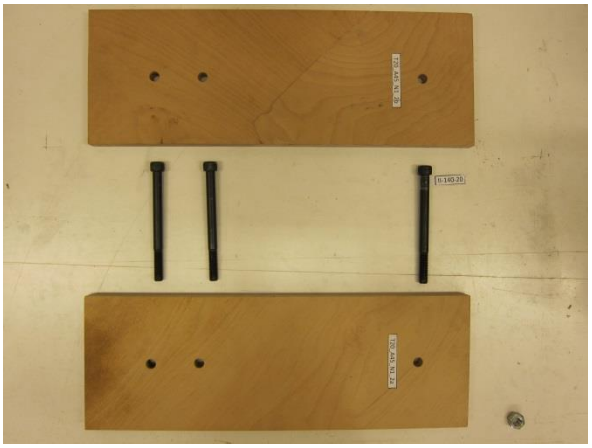


Figure 401 Overview materials

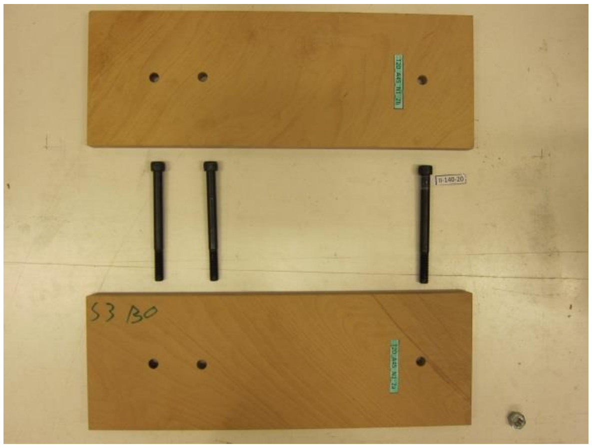


Figure 402 Overview materials

<u>After testing</u>

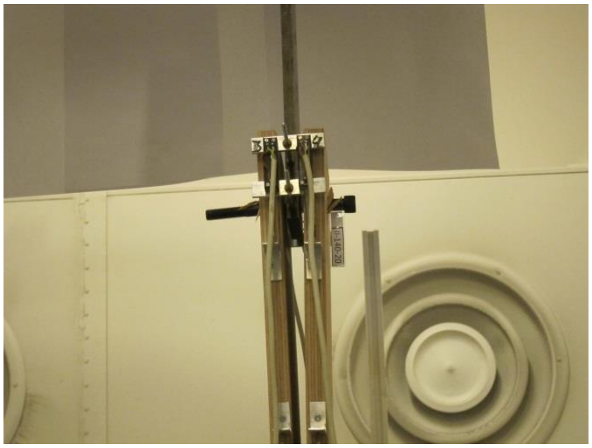


Figure 403 Front view


Figure 404 Perspective view nr. 1

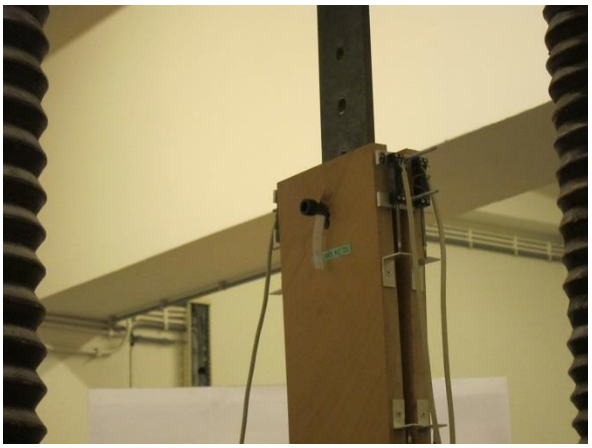


Figure 405 Perspective view nr. 2

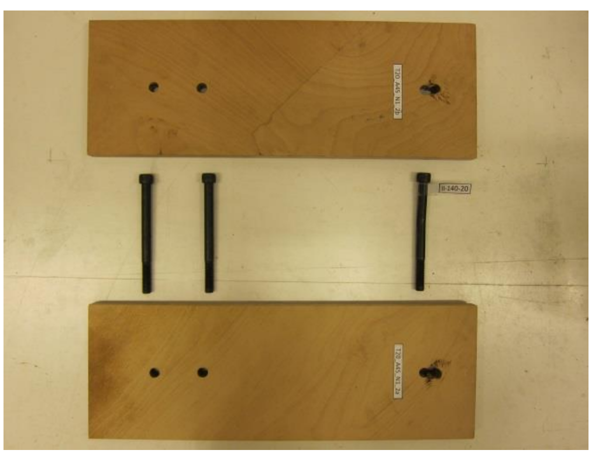


Figure 406 Overview materials

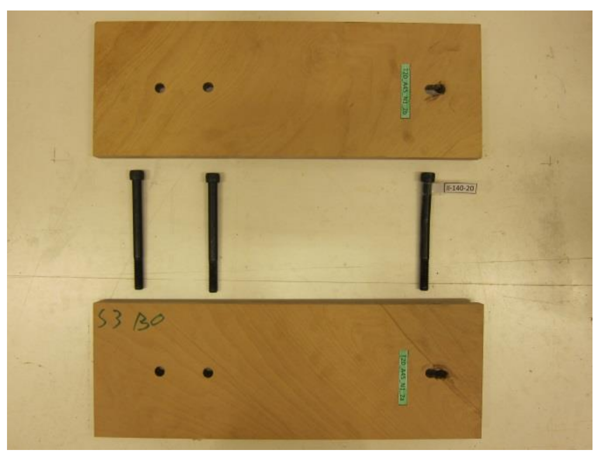


Figure 407 Overview materials

Figure 408 Closeup failure(Surface towards steel plate)

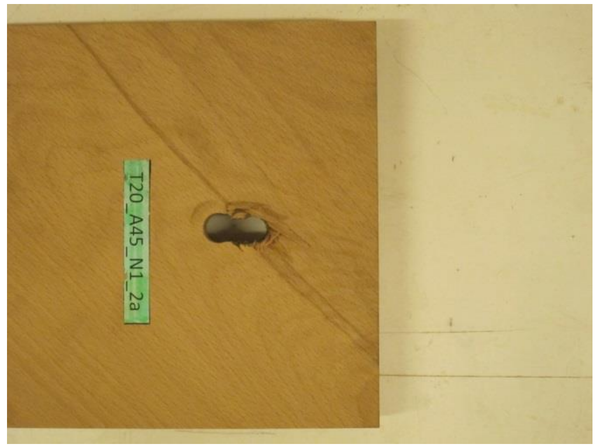


Figure 410 Closeup failure(Surface on the outside)

Figure 409 Closeup failure(Surface towards steel plate))

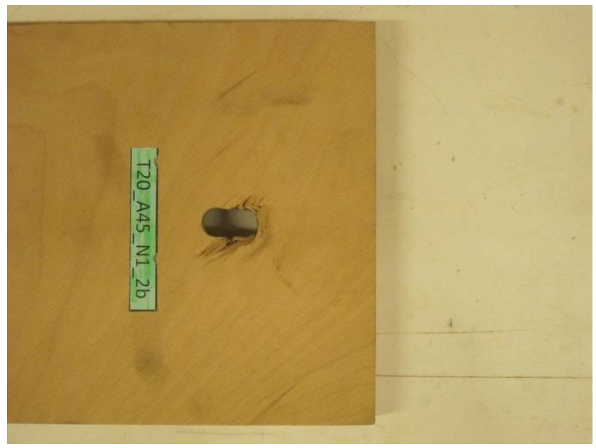


Figure 411 Closeup failure(Surface on the outside)

Figure 412 Dowels after testing strengthened side

Figure 413 Dowels after testing test side

13.10.1 T20_A45_N1_1

Material coding:

Labels Timber	T20_A45_N1_1a	T20_A45_N1_1b
Labels Steel Test side	I-190-1	
Labels Steel Strengthened. side	reused	

Table 127 Material coding T20_A45_N1_1

Log:

Material: *Clear specimen, with some surface discolouration*
F_{est}: *35kN*
Displacement controlled speed(1): *0.014mm/s*
Displacement controlled speed(2): *mm/s*

During testing: *as planned*

Cause of failure: *embedment failure*

Additional remarks:

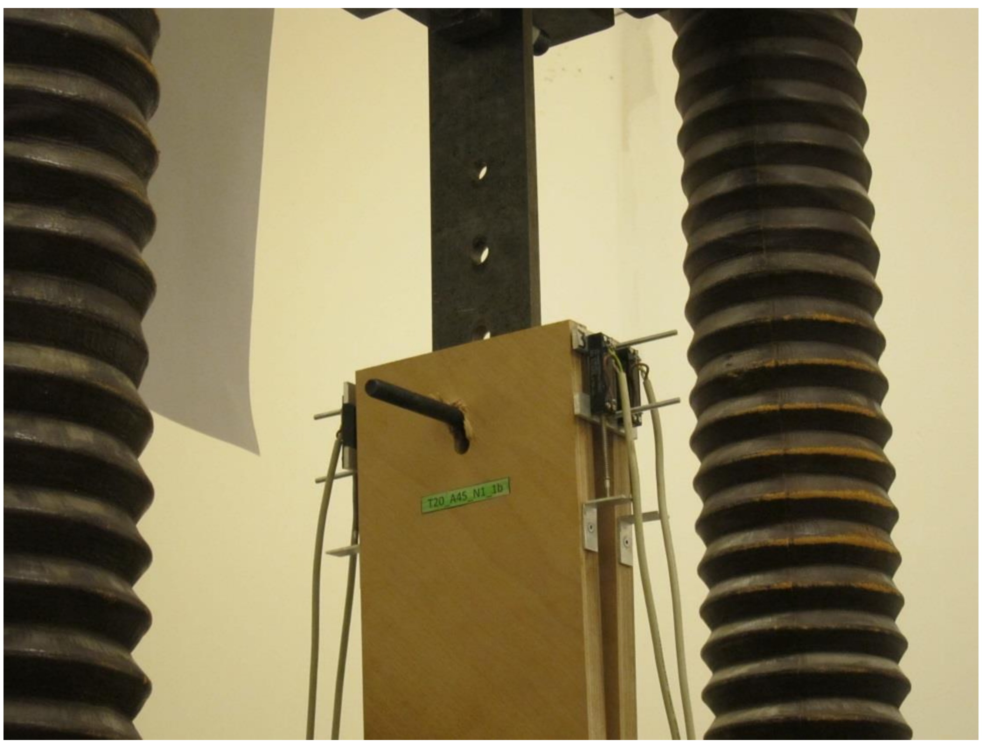


Figure 414 Perspective view nr1. After testing

Data:

T20_A45_N1_1	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	48,33	10,94	1,75	14,31	21,86
$F_{0,5}$	41,94	5,00	1,53	8,01	14,37
$F_{failure}$	-	-	-	-	-

Table 128 Results of specimen T20_A45_N1_1

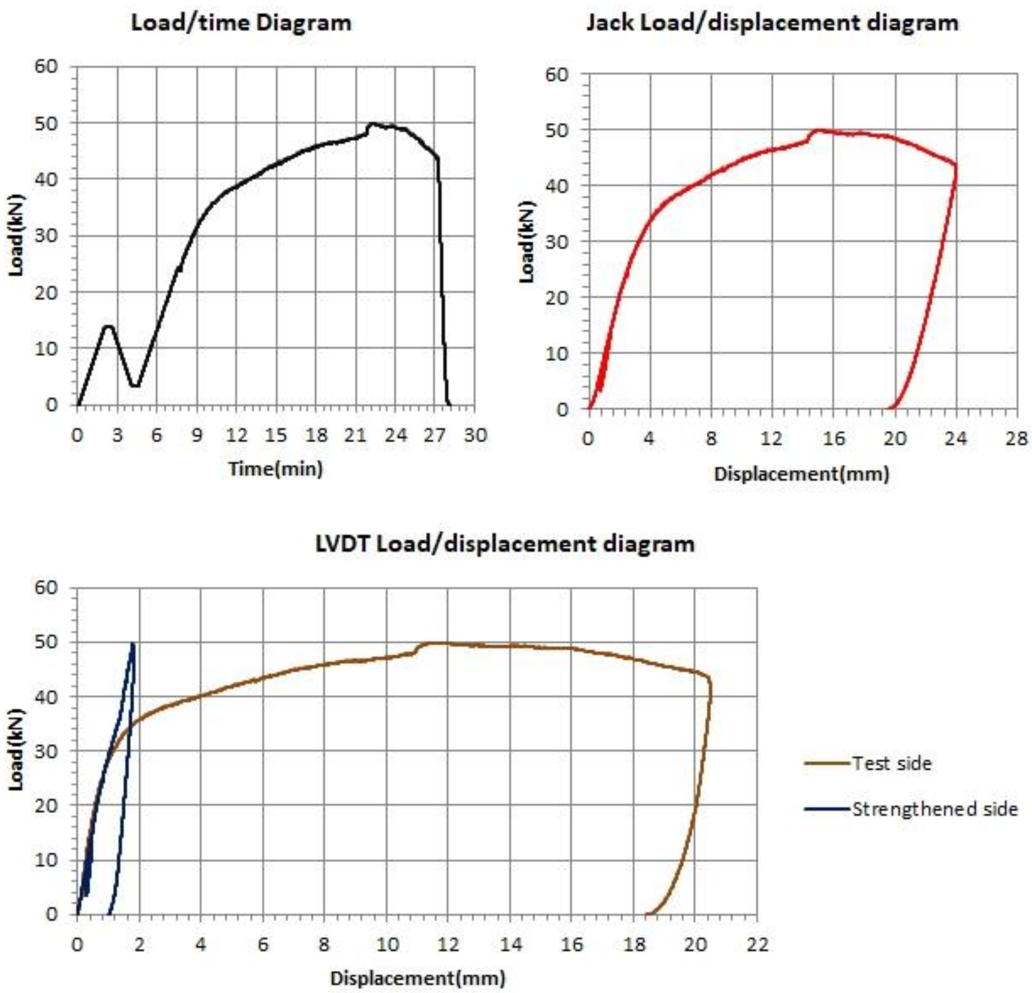


Figure 415 Graphical results of T20_A45_N1_1

13.10.2 T20_A45_N1_2

Material coding:

Labels Timber	T20_A45_N1_2a	T20_A45_N1_2b
Labels Steel Test side	II-140-20	
Labels Steel Strengthened. side	new	

Table 129 Material coding T20_A45_N1_2

Log:

Material: *clear specimen*

F_{est}: *50kN*
Displacement controlled speed(1): *0.03mm/s*
Displacement controlled speed(2): *-mm/s*

During testing: *as planned*

Cause of failure: *embedment failure*

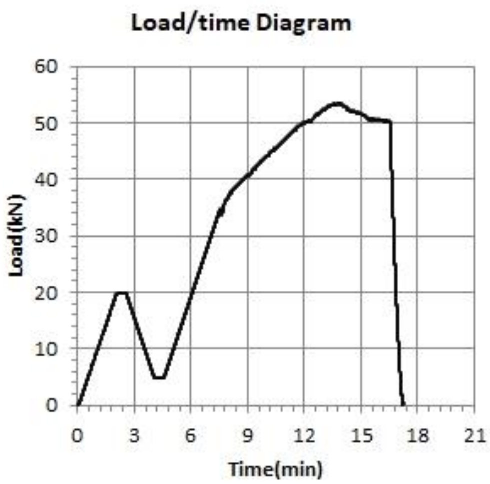
Additional remarks: *holes at strengthened side re-drilled due to error in spacing.*

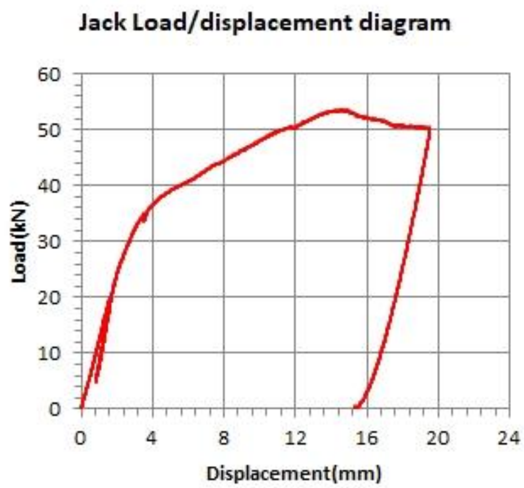
Figure 416 Perspective view nr1. After testing

Data:

T20_A45_N1_2	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	53,50	11,80	1,39	14,84	13,92
$F_{0,5}$	43,66	5,00	1,14	7,43	9,81
$F_{failure}$	-	-	-	-	-

Table 130 Results of specimen T20_A45_N1_2





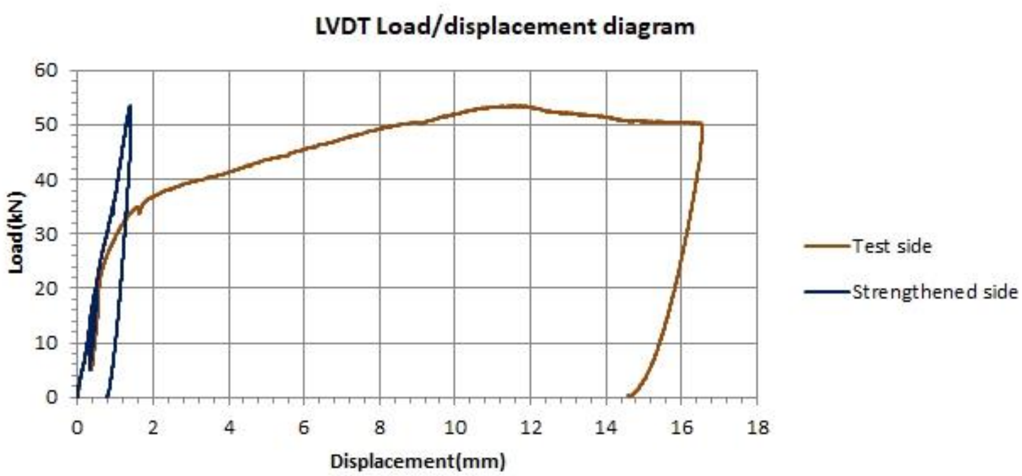


Figure 417 Graphical results of T20_A45_N1_2

13.10.3 T20_A45_N1_3

Material coding:

Labels Timber	T20_A45_N1_3a	T20_A45_N1_3b
Labels Steel Test side	II-140-21	
Labels Steel Strengthened. side	new	

Table 131 Material coding T20_A45_N1_3

Log:

Material: *Top layer specimen a very thin.*

F_{est}: *50kN*
Displacement controlled speed(1): *0.03mm/s*
Displacement controlled speed(2): *-mm/s*

During testing: *as planned*

Cause of failure: *embedment failure*

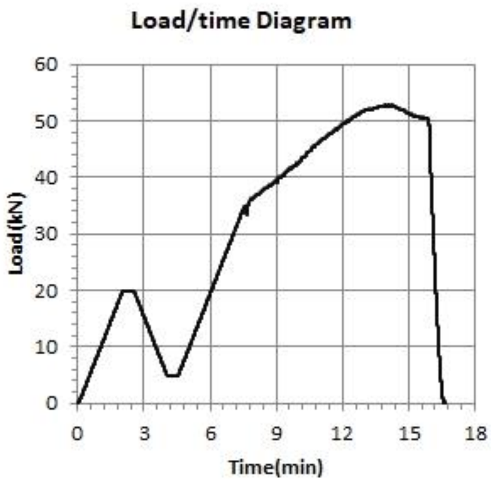
Additional remarks: *holes at strengthened side re-drilled due to error in spacing.*

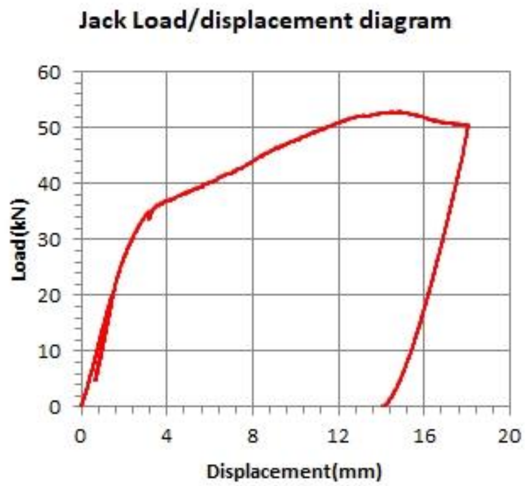
Figure 418 Perspective view nr1. After testing

Data:

T20_A45_N1_3	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	52,87	12,46	0,80	14,83	14,13
$F_{0,5}$	41,71	5,00	0,58	6,78	9,65
$F_{failure}$	-	-	-	-	-

Table 132 Results of specimen T20_A45_N1_3





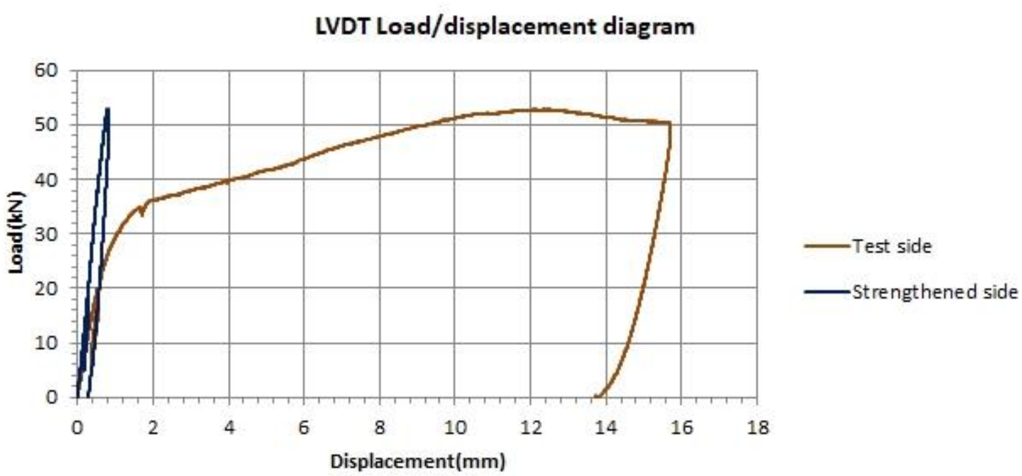


Figure 419 Graphical results of T20_A45_N1_3

13.11 T20_A90_N1

Before Testing(pictures test specimen T20_A90_N1_3 shear failure):

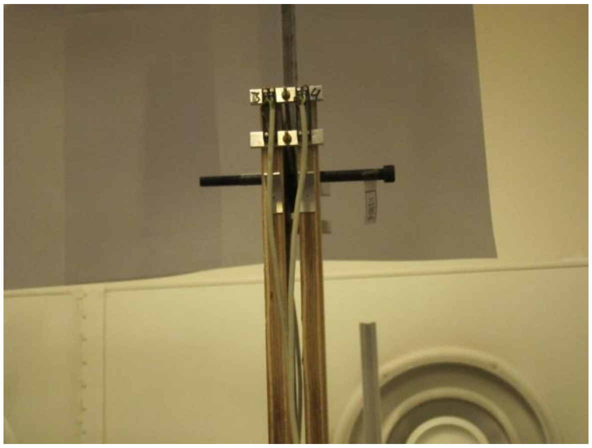


Figure 420 Front view

Figure 421 Perspective view nr. 1

Figure 422 Perspective view nr 2

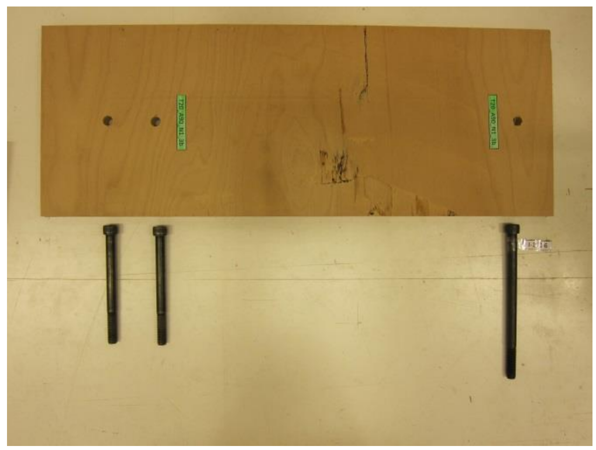


Figure 423 Overview materials

Figure 424 Overview materials

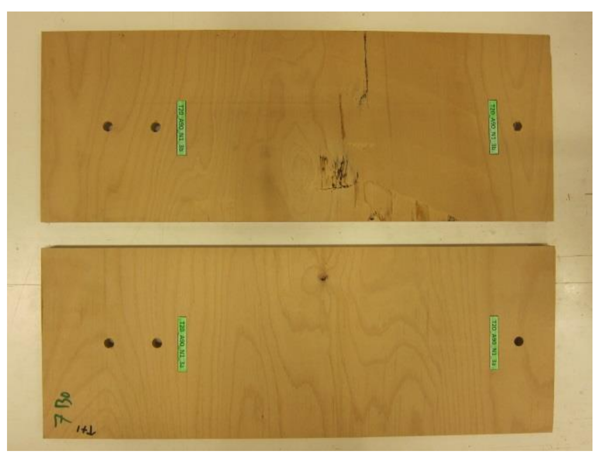


Figure 425 Overview materials

After testing

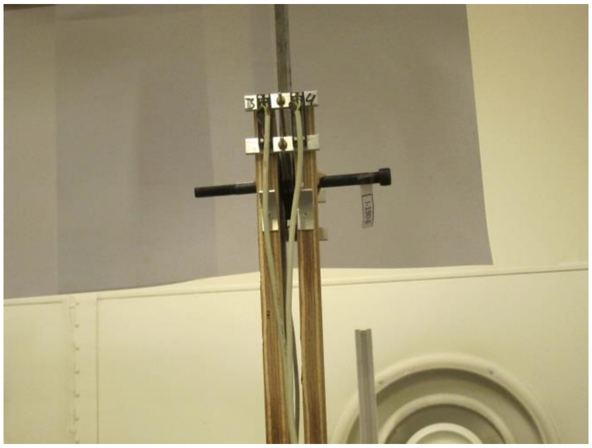


Figure 426 Front view

Figure 427 Perspective view nr. 1

Figure 428 Perspective view nr. 2

Figure 429 Overview materials

Figure 430 Overview materials

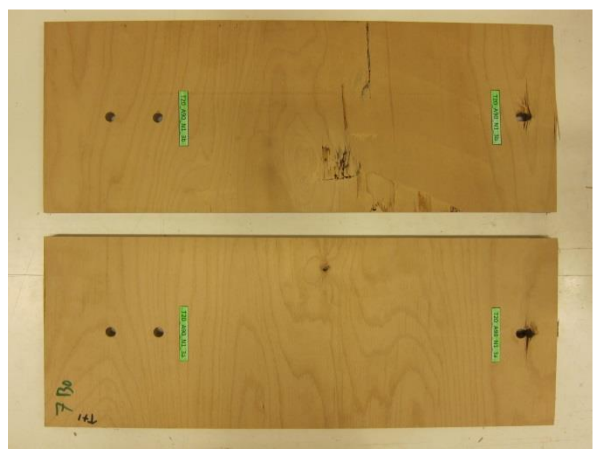


Figure 431 Overview materials

Figure 432 Closeup failure(Surface towards steel plate)

Figure 434 Closeup failure(Surface on the outside)

Figure 433 Closeup failure(Surface towards steel plate))

Figure 435 Closeup failure(Surface on the outside)

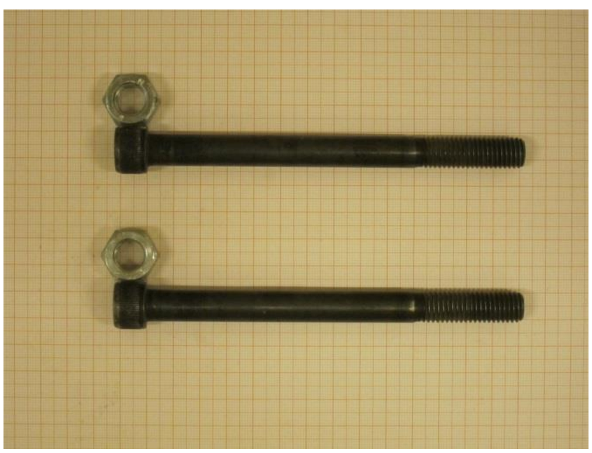


Figure 436 Dowels after testing strengthened side

Figure 437 Dowels after testing test side

13.11.1 T20_A90_N1_1

Material coding:

Labels Timber	T20_A90_N1_1a	T20_A90_N1_1b
Labels Steel Test side	I-190-4	
Labels Steel Strengthened. side	reused	reused

Table 133 Material coding T20_A90_N1_1

Log:

Material: *knots present in specimen a and top layer damaged, specimen b clear specimen*

F_{est}: *35kN*
Displacement controlled speed(1): *0.0125mm/s*
Displacement controlled speed(2): *0.025mm/s*

During testing: *as planned, but test was rather slow*

Cause of failure: *shear failure*

Additional remarks:

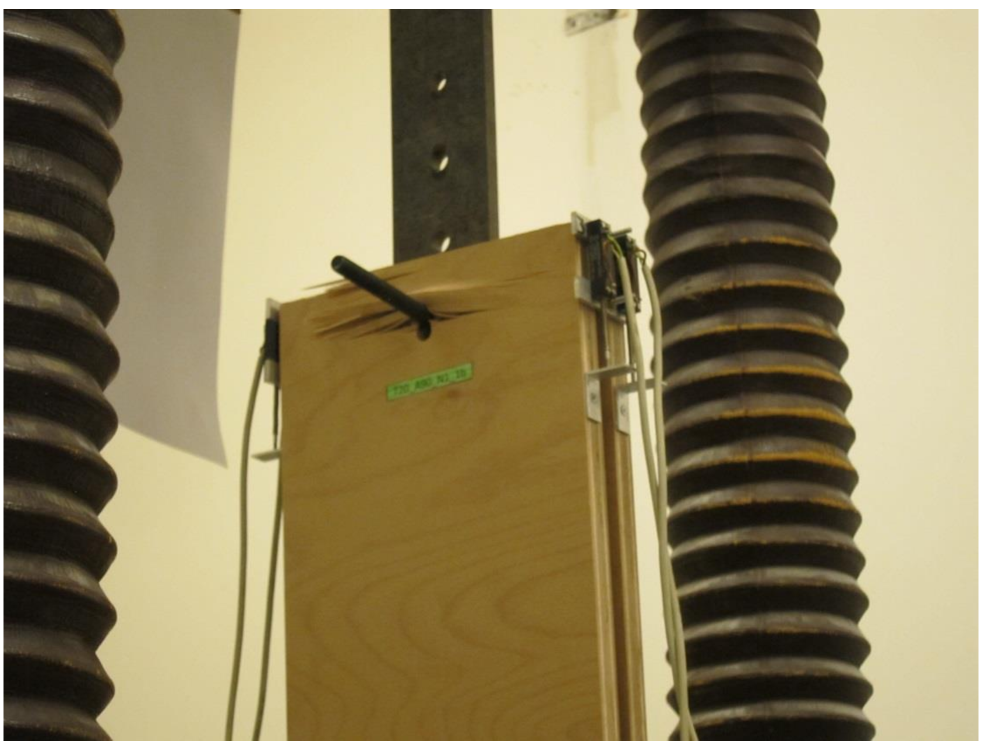
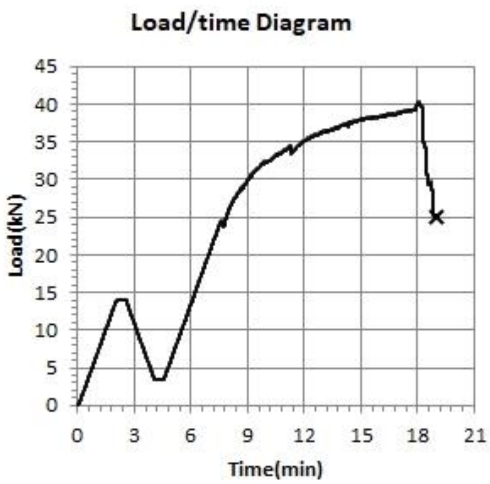


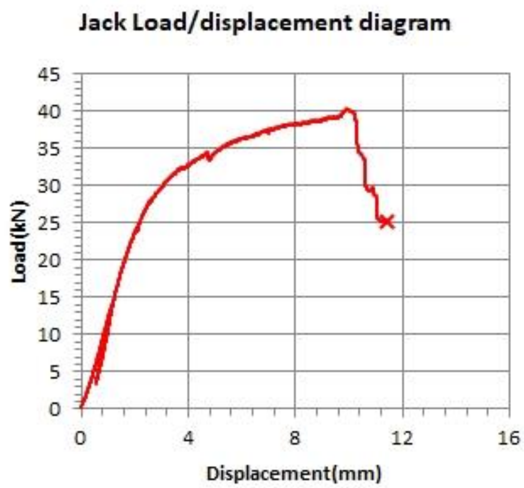
Figure 438 Perspective view nr1. After testing

Data:

T20_A90_N1_1	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	40,31	7,76	0,75	9,90	18,03
$F_{0,5}$	37,36	5,00	0,71	6,91	14,18
$F_{failure}$	25,00	9,75	0,68	11,46	19,08

Table 134 Results of specimen T20_A90_N1_1





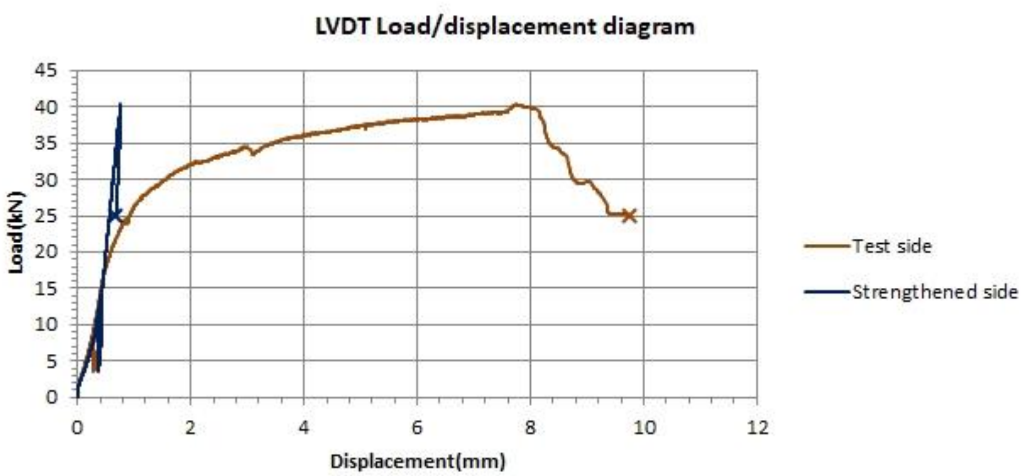


Figure 439 Graphical results of T20_A90_N1_1

13.11.2 T20_A90_N1_2

Material coding:

Labels Timber	T20_A90_N1_2a	T20_A90_N1_2b
Labels Steel Test side	I-190-5	
Labels Steel Strengthened. side	reused	reused

Table 135 Material coding T20_A90_N1_2

Log:

Material: *clear specimen*

F_{est}: *40kN*
Displacement controlled speed(1): *0.016mm/s*
Displacement controlled speed(2): *mm/s*

During testing: *as planned*

Cause of failure: *shear failure*

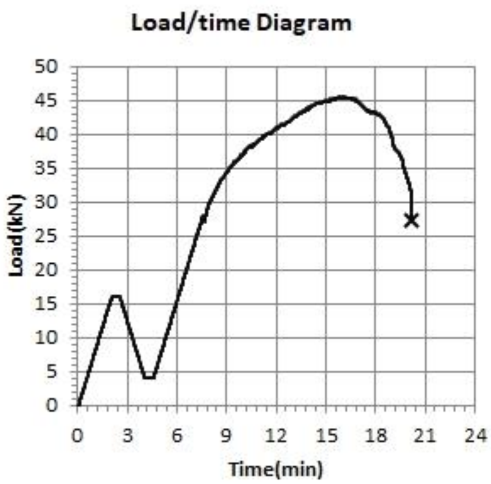
Additional remarks:

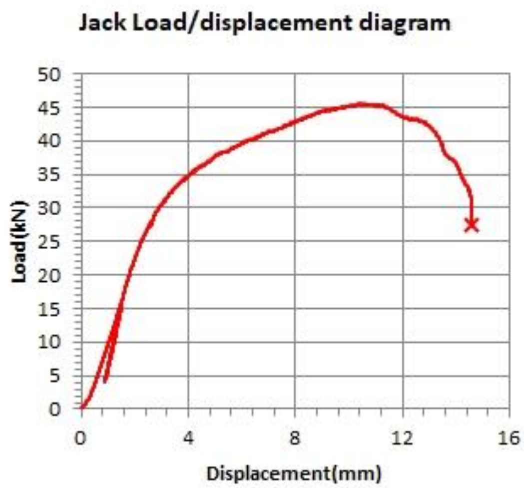
Figure 440 Perspective view nr1. After testing

Data:

T20_A90_N1_2	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	45,58	7,80	1,10	10,39	15,79
$F_{0,5}$	41,78	5,00	0,98	7,33	12,60
$F_{failure}$	27,31	12,61	1,08	14,62	20,20

Table 136 Results of specimen T20_A90_N1_2





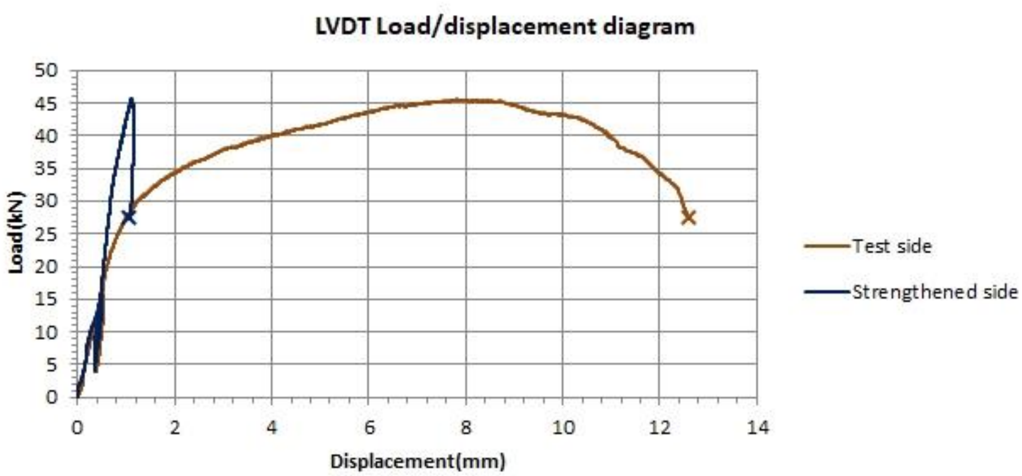


Figure 441 Graphical results of T20_A90_N1_2

13.11.3 T20_A90_N1_3

Material coding:

Labels Timber	T20_A90_N1_3a	T20_A90_N1_3b
Labels Steel Test side	I-190-6	
Labels Steel Strengthened. side	reused	reused

Table 137 Material coding T20_A90_N1_3

Log:

Material: *clear specimen*

F_{est}: *45kN*

Displacement controlled speed(1): *0.02mm/s*

Displacement controlled speed(2): *mm/s*

During testing: *as planned*

Cause of failure: *shear failure*

Additional remarks:

Figure 442 Perspective view nr1. After testing

Data:

T20_A90_N1_3	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	48,54	7,29	0,99	9,68	13,52
$F_{0,5}$	45,00	5,00	0,87	7,16	11,41
$F_{failure}$	26,01	12,90	0,89	14,68	17,69

Table 138 Results of specimen T20_A90_N1_3

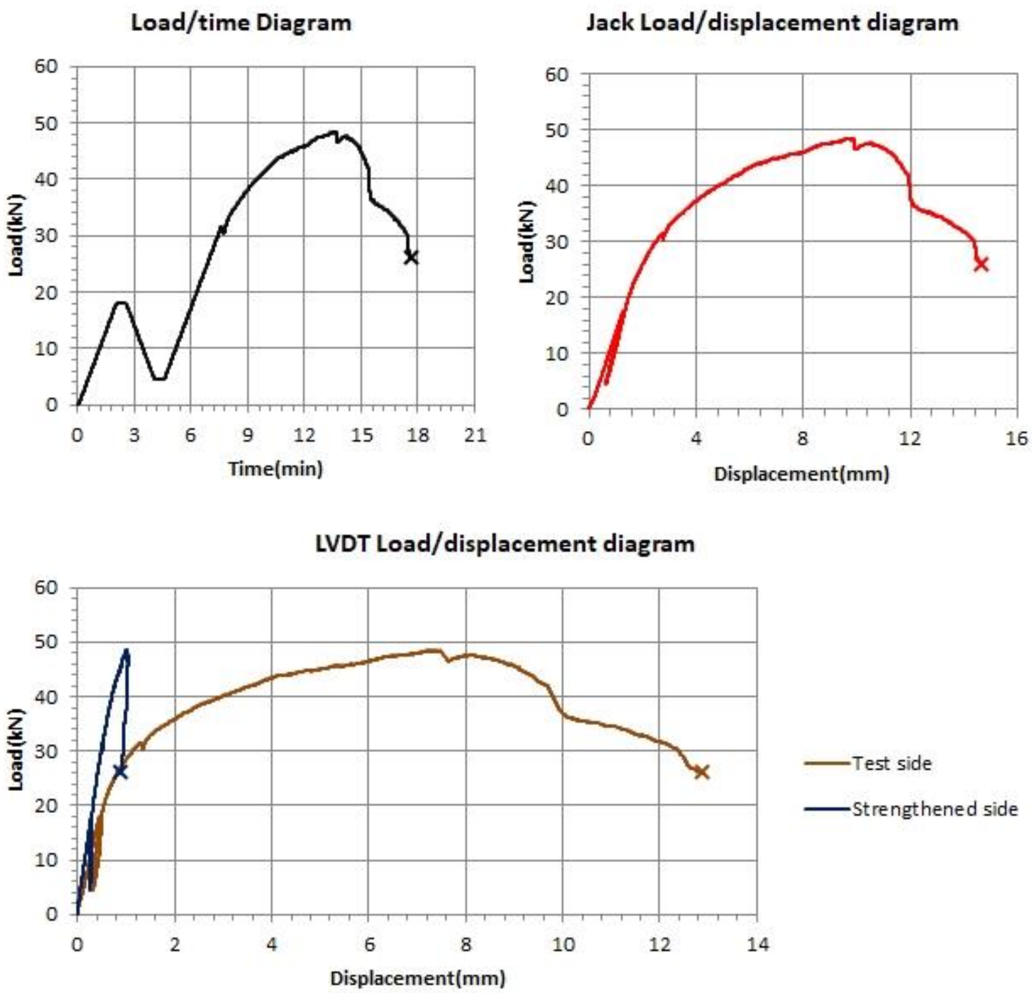


Figure 443 Graphical results of T20_A90_N1_3

13.11.4 T20_A90_N1_4

Material coding:

Labels Timber	T20_A90_N1_4a	T20_A90_N1_4b
Labels Steel Test side	I-190-7	
Labels Steel Strengthened. side	reused	reused

Table 139 Material coding T20_A90_N1_4

Log:

Material: *clear specimen*

F_{est}: *45kN*
Displacement controlled speed(1): *mm/s*
Displacement controlled speed(2): *mm/s*

During testing: *as planned*

Cause of failure: *shear failure*

Additional remarks:

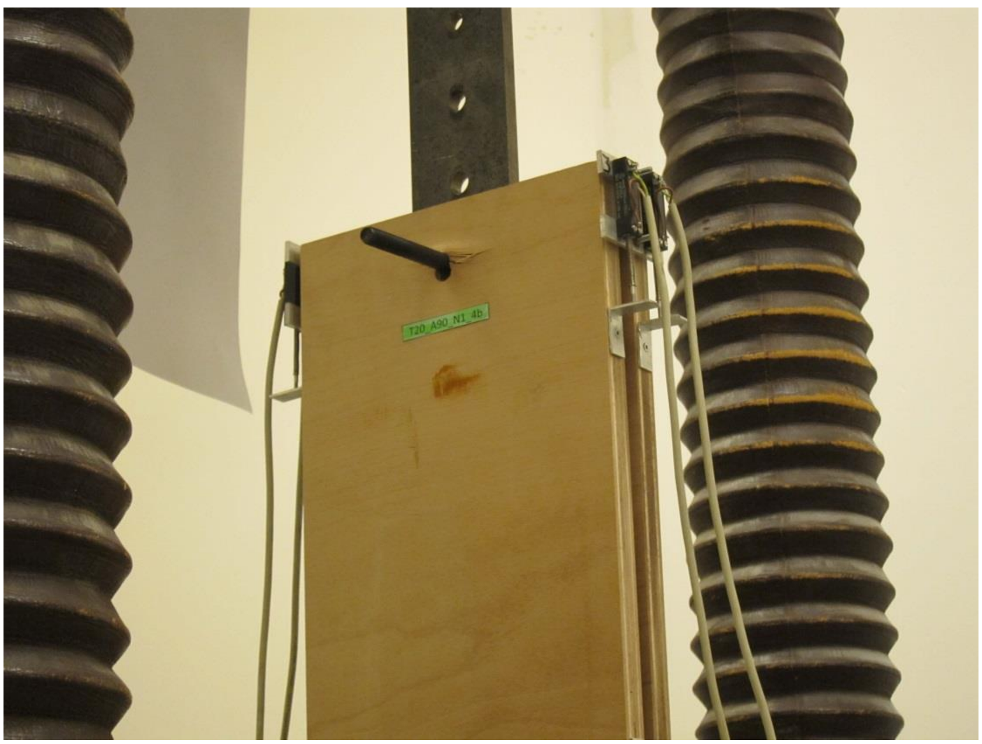
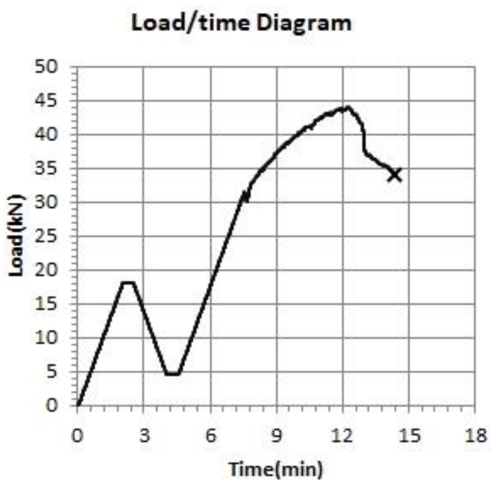


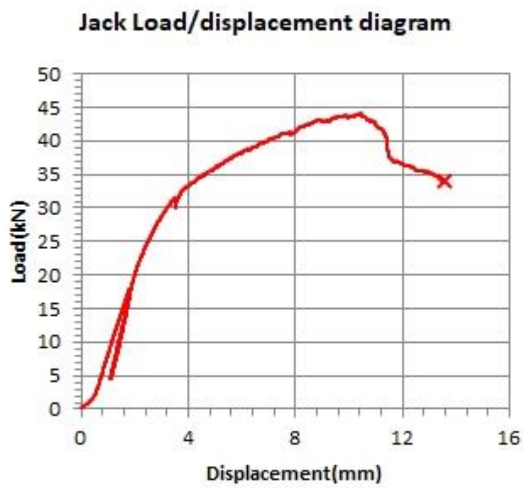
Figure 444 Perspective view nr1. After testing

Data:

T20_A90_N1_4	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	44,11	7,77	1,00	10,42	12,29
$F_{0,5}$	40,90	5,00	0,89	7,45	10,32
$F_{failure}$	33,83	11,19	1,00	13,57	14,41

Table 140 Results of specimen T20_A90_N1_4





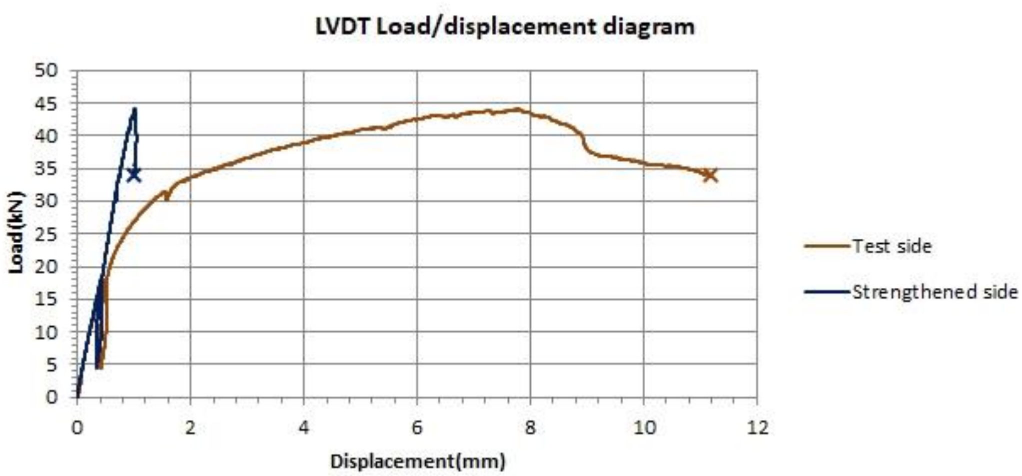


Figure 445 Graphical results of T20_A90_N1_4

13.11.5 T20_A90_N1_5

Material coding:

Labels Timber	T20_A90_N1_5a	T20_A90_N1_5b
Labels Steel Test side	I-190-8	
Labels Steel Strengthened. side	reused	reused

Table 141 Material coding T20_A90_N1_5

Log:

Material: *small defects*

F_{est}: *45kN*

Displacement controlled speed(1): *0.02mm/s*

Displacement controlled speed(2): *mm/s*

During testing: *Error in data recordings. Restarted test after reaching 9 kN. After tests concluded voltage of LVDT's was incorrect leading to bad displacement data*

Cause of failure: **-**

Additional remarks:

Figure 446 Perspective view nr1. After testing(zoomed in)

Data:

T20_A90_N1_5	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	48,51	-	-	9,49	13,39
$F_{0,5}$	-	-	-	-	-
$F_{failure}$	32,11	-	-	12,21	15,66

Table 142 Results of specimen T20_A90_N1_5(LVDT's unusable due to incorrect voltage)

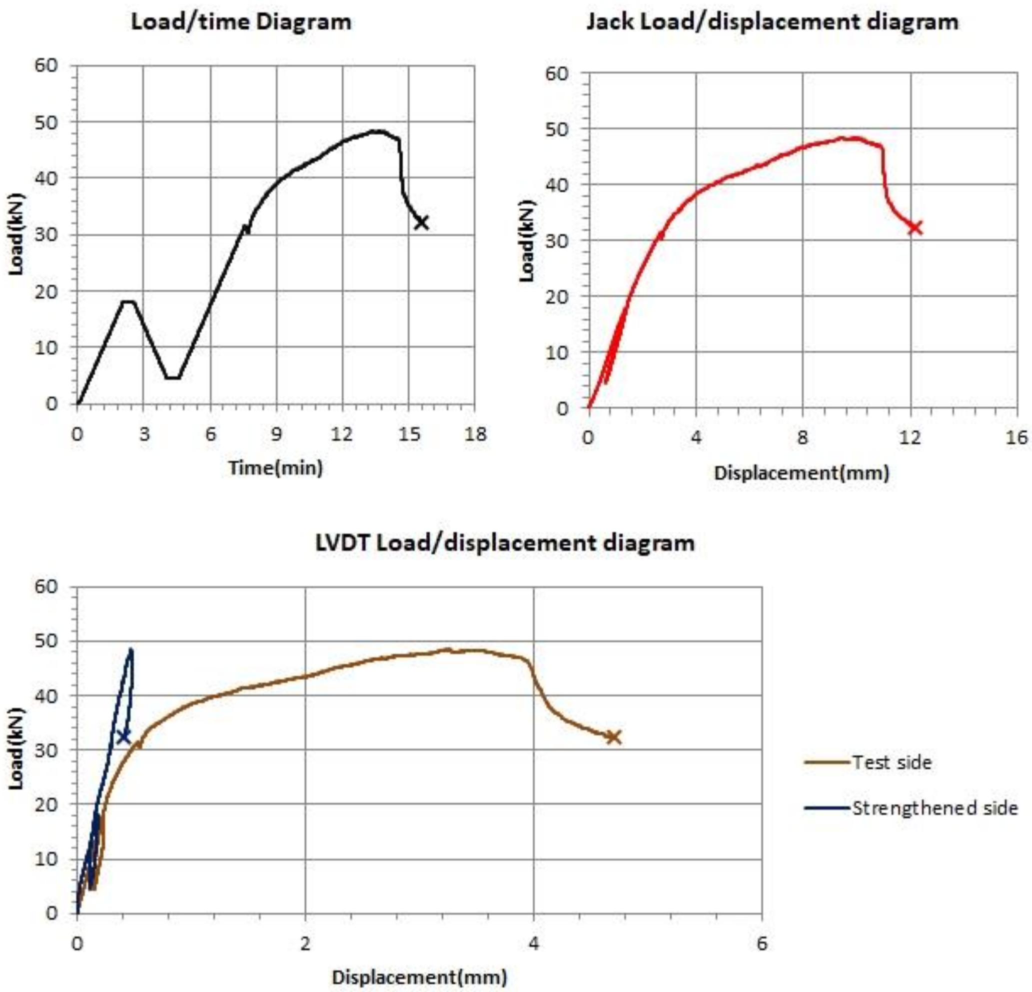


Figure 447 Graphical results of T20_A90_N1_5

13.12 T20_A90_N2

***Before Testing*(pictures test specimen T20_A90_N2_5 tensile failure):**

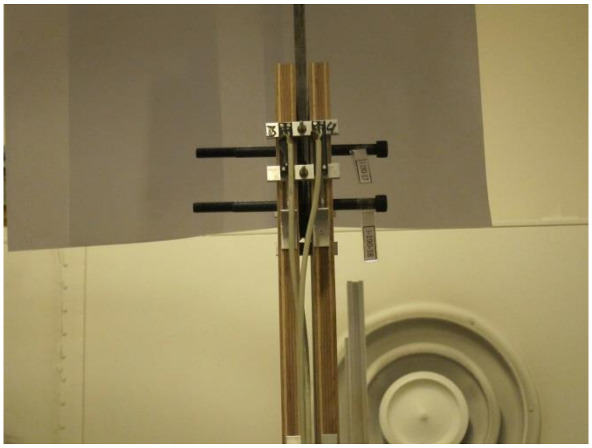


Figure 448 Front view

Figure 449 Perspective view nr. 1

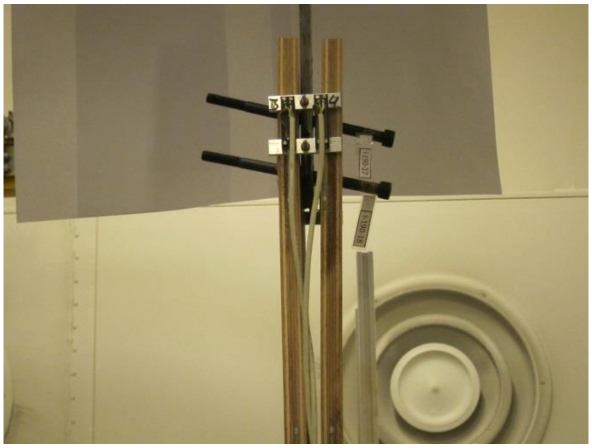
Figure 450 Perspective view nr 2

Figure 451 Overview material

Figure 452 Overview materials

Figure 453 Overview materials

After testing



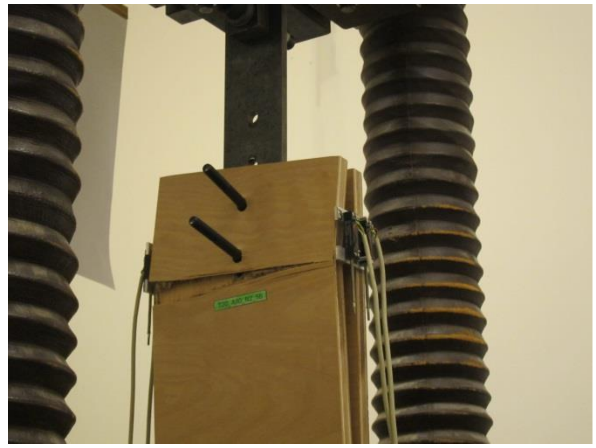


Figure 454 Front view

Figure 455 Perspective view nr. 1

Figure 456 Perspective view nr. 2

Figure 457 Overview materials

Figure 458 Overview materials

Figure 459 Closeup failure(Surface towards steel plate)

Figure 461 Closeup failure(Surface on the outside)

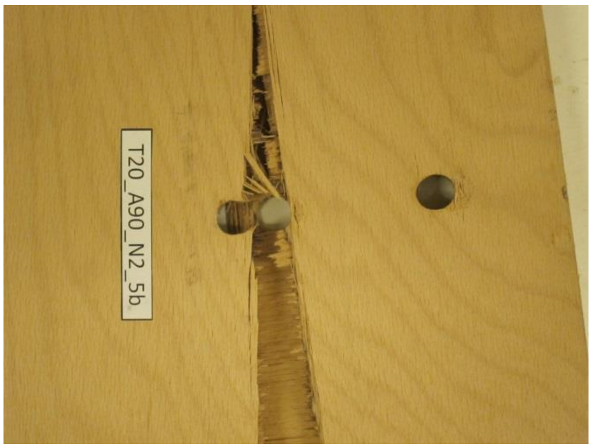


Figure 460 Closeup failure(Surface towards steel plate))

Figure 462 Closeup failure(Surface on the outside)

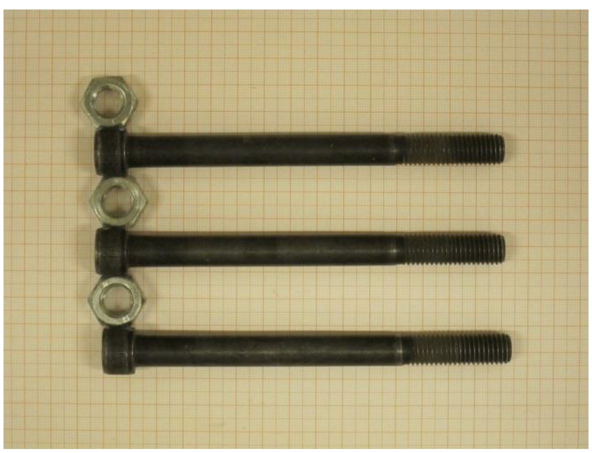


Figure 463 Dowels after testing strengthened side

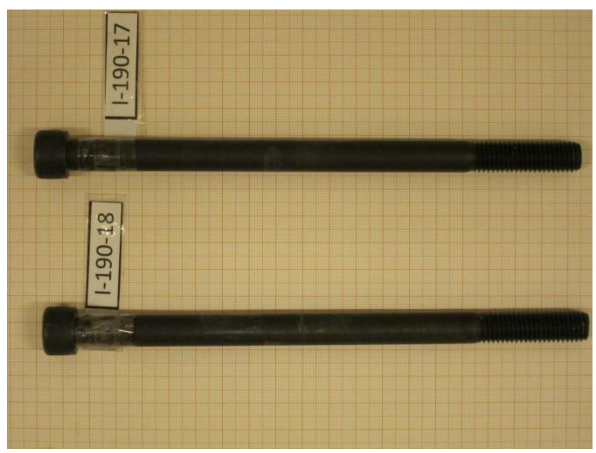


Figure 464 Dowels after testing test side

13.12.1 T20_A90_N2_1

Material coding:

Labels Timber	T20_A90_N2_1a	T20_A90_N2_1b	
Labels Steel Test side	I-190-9	I-190-10	
Labels Steel Strengthened. side	reused	reused	reused

Table 143 Material coding T20_A90_N2_1

Log:

Material: *Clear specimen*

F_{est}: *80kN*
Displacement controlled speed(1): *0.03mm/s*
Displacement controlled speed(2): *mm/s*

During testing: *as planned*

Cause of failure: *tensile failure*

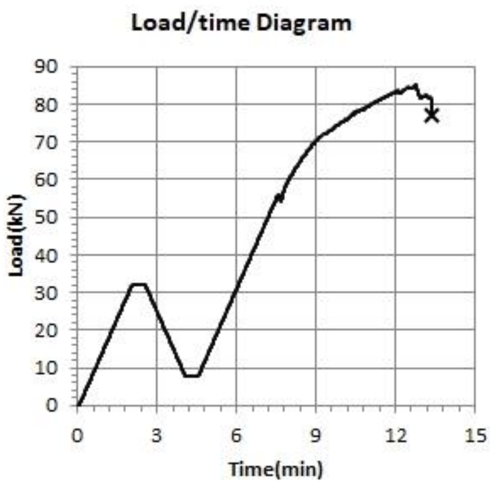
Additional remarks: *small veneer sheared out during testing before failure*

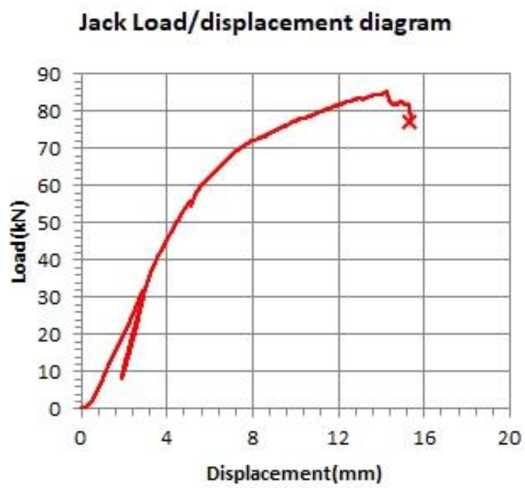
Figure 465 Perspective view nr1. After testing

Data:

T20_A90_N2_1	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	85,16	8,40	3,33	14,25	12,78
$F_{0,5}$	77,81	5,00	2,83	10,15	10,50
$F_{failure}$	76,72	9,70	3,36	15,38	13,40

Table 144 Results of specimen T20_A90_N2_1





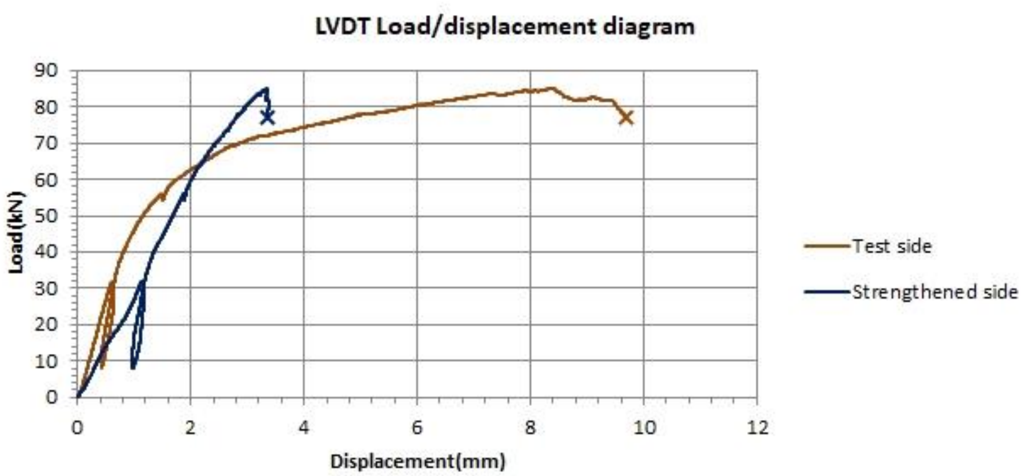


Figure 466 Graphical results of T20_A90_N2_1

13.12.2 T20_A90_N2_2

Material coding:

Labels Timber	T20_A90_N2_2a	T20_A90_N2_2b	
Labels Steel Test side	I-190-11	I-190-12	
Labels Steel Strengthened. side	reused	reused	reused

Table 145 Material coding T20_A90_N2_2

Log:

Material: *top layer specimen a partially damaged*

F_{est}: *85kN*

Displacement controlled speed(1): *0.03mm/s*

Displacement controlled speed(2): *mm/s*

During testing: *switched earlier to displacement controlled due to lots of cracking noise, around 52kN the switch was made instead of 58.*

Cause of failure: *tensile failure*

Additional remarks:

Figure 467 Perspective view nr2. After testing

Data:

T20_A90_N2_2	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	77,63	8,11	2,68	12,85	13,83
$F_{0,5}$	68,40	5,00	2,38	9,15	10,75
$F_{failure}$	67,91	8,52	2,72	12,95	15,48

Table 146 Results of specimen T20_A90_N2_2

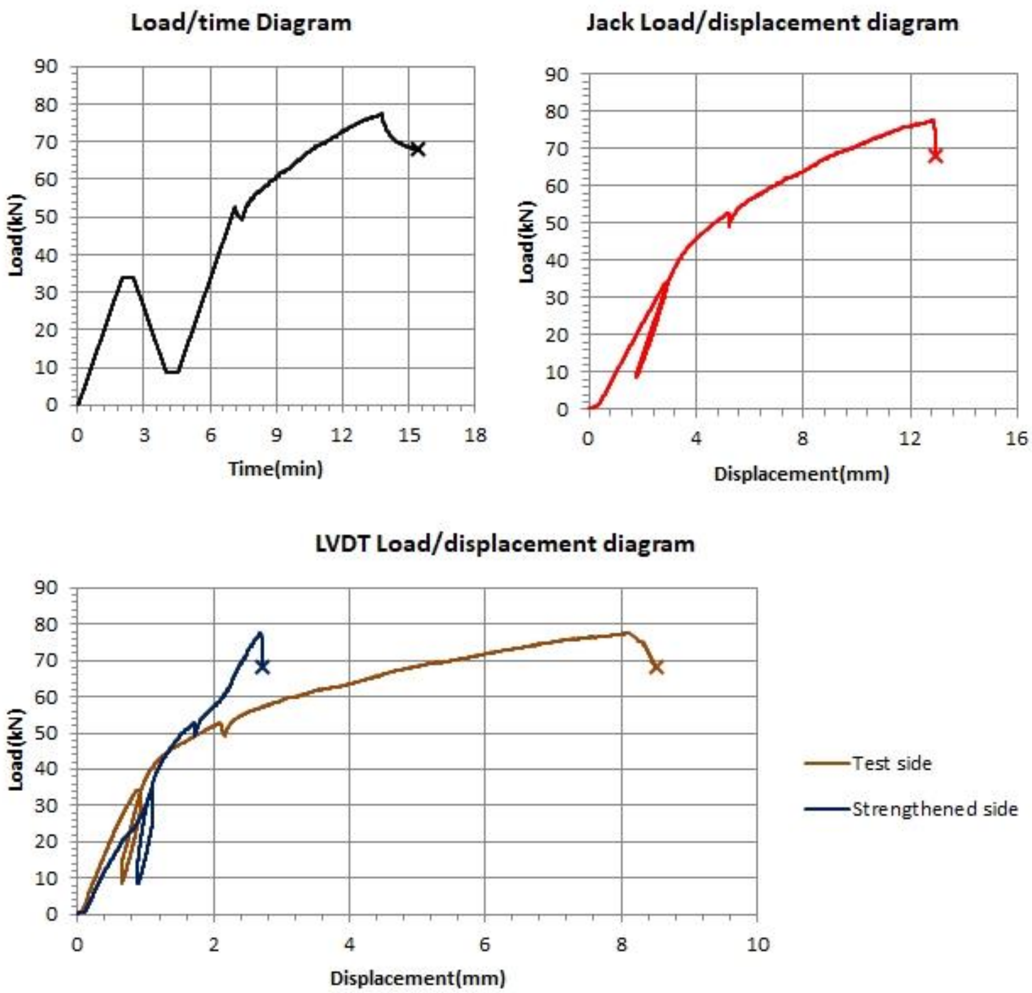


Figure 468 Graphical results of T20_A90_N2_2

13.12.3 T20_A90_N2_3

Material coding:

Labels Timber	T20_A90_N2_3a	T20_A90_N2_3b	
Labels Steel Test side	I-190-13	I-190-14	
Labels Steel Strengthened. side	reused	reused	reused

Table 147 Material coding T20_A90_N2_3

Log:

Material: *clear specimen*

F_{est}: *80kN*

Displacement controlled speed(1): *0.025mm/s*

Displacement controlled speed(2): *mm/s*

During testing: *as planned*

Cause of failure: *tensile failure*

Additional remarks:

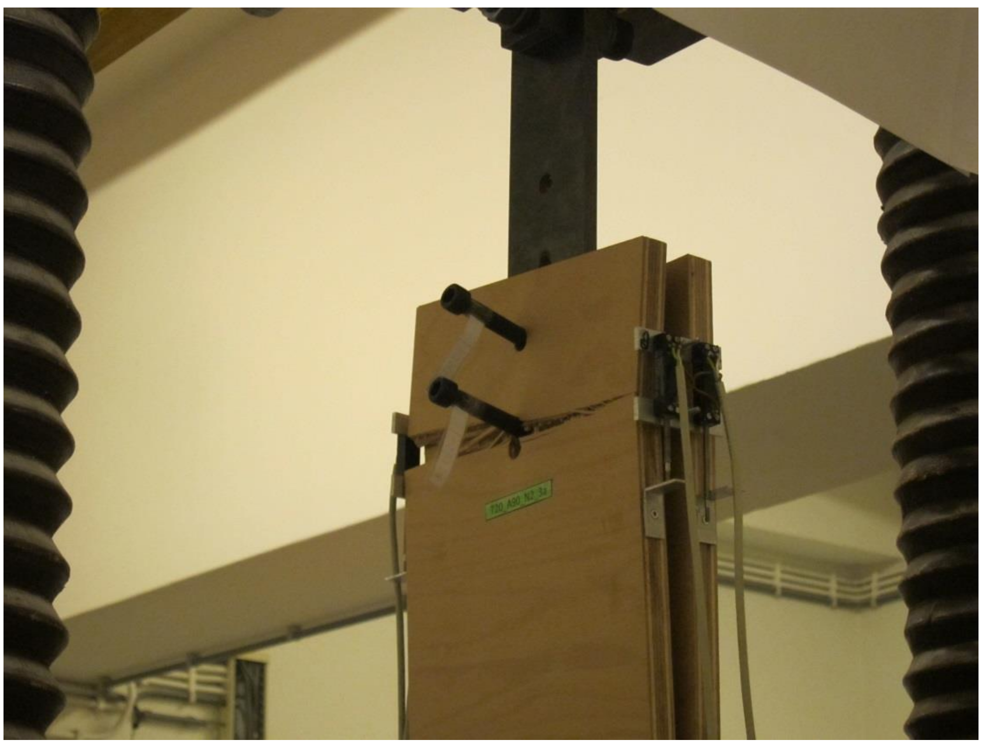
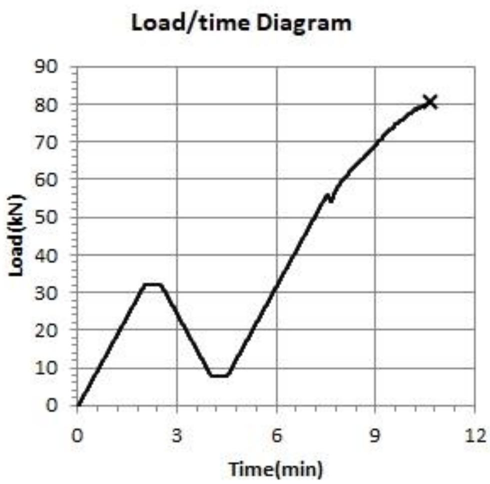


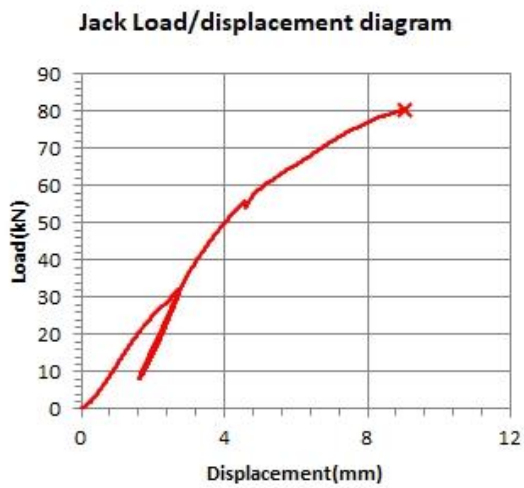
Figure 469 Perspective view nr2. After testing

Data:

T20_A90_N2_3	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	80,68	4,03	2,84	9,05	10,65
$F_{0,5}$	-	-	-	-	-
$F_{failure}$	80,29	4,05	2,84	9,07	10,66

Table 148 Results of specimen T20_A90_N2_3





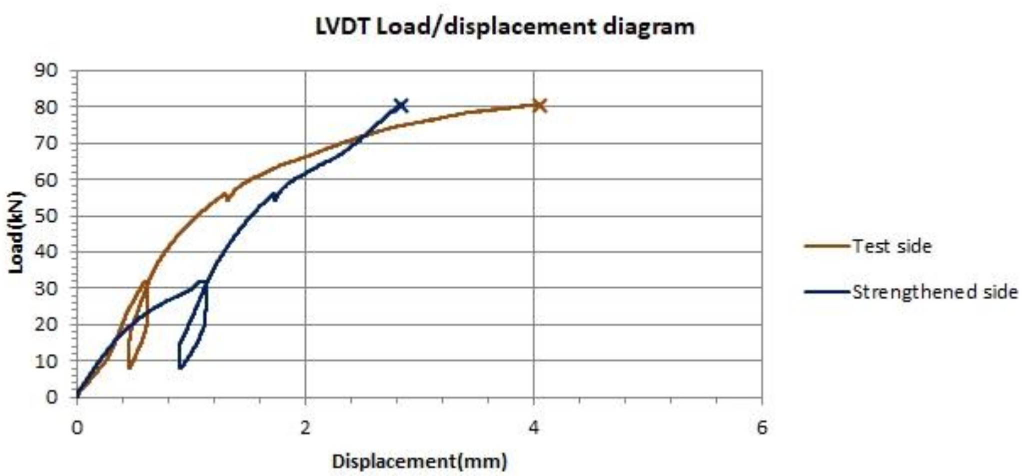


Figure 470 Graphical results of T20_A90_N2_3

13.12.4 T20_A90_N2_4

Material coding:

Labels Timber	T20_A90_N2_4a	T20_A90_N2_4b	
Labels Steel Test side	I-190-15	I-190-16	
Labels Steel Strengthened. side	reused	reused	reused

Table 149 Material coding T20_A90_N2_4

Log:

<u>Material</u>: *clear specimen*

<u>F_{est}:</u> *80kN*
<u>Displacement controlled speed(1):</u> *0.025mm/s*
<u>Displacement controlled speed(2):</u> *mm/s*

<u>During testing</u>: *see remark, after some thought it might have been better to continue testing until the full failure occurred.*

<u>Cause of failure:</u> *-*

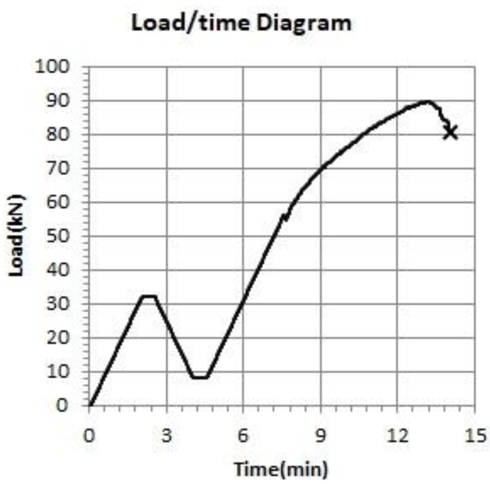
<u>Additional remarks:</u> *This test was halted earlier to see the effective area which resists shear, as the failure seem to occur less rapidly than other experiments*

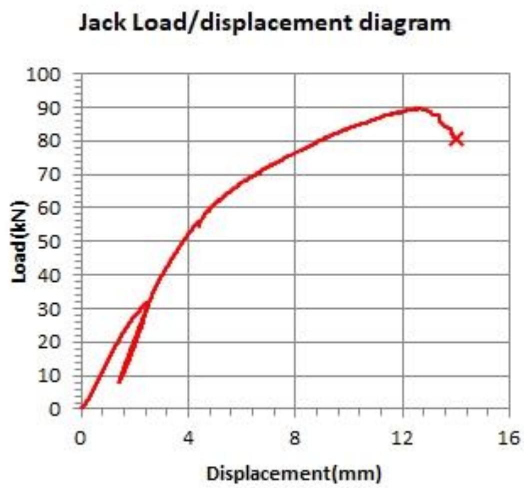
Figure 471 Closeup. After testing

Data:

T20_A90_N2_4	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	89,83	7,43	2,90	12,68	13,20
$F_{0,5}$	83,40	5,00	2,72	9,90	11,35
$F_{failure}$	80,30	8,91	2,90	14,02	14,10

Table 150 Results of specimen T20_A90_N2_4





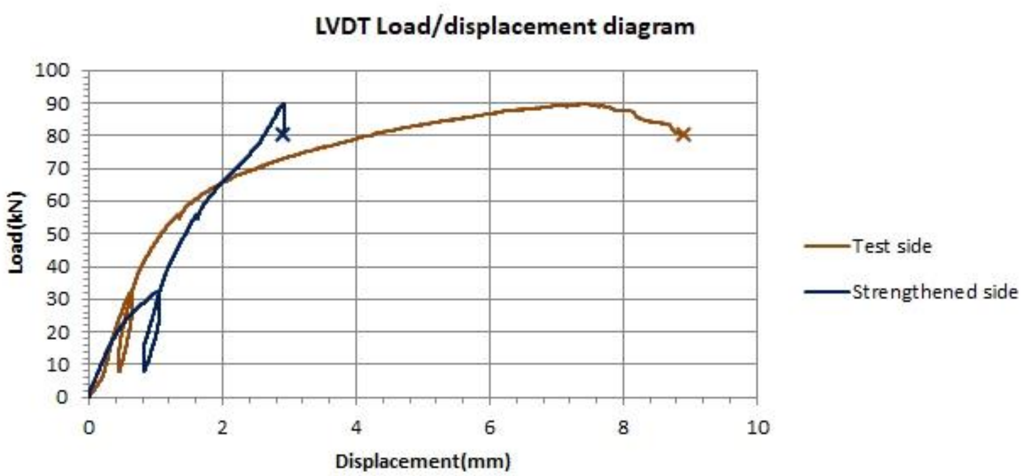


Figure 472 Graphical results of T20_A90_N2_4

13.12.5 T20_A90_N2_5

Material coding:

Labels Timber	T20_A90_N2_5a	T20_A90_N2_5b	
Labels Steel Test side	I-190-17	I-190-18	
Labels Steel Strengthened. side	reused	reused	reused

Table 151 Material coding T20_A90_N2_5

Log:

<u>Material</u>: *clear specimen*

<u>F_{est}:</u> *80kN*
<u>Displacement controlled speed(1):</u> *0.025mm/s*
<u>Displacement controlled speed(2):</u> *mm/s*

<u>During testing</u>: *as planned*

<u>Cause of failure:</u> *tensile failure*

<u>Additional remarks:</u>

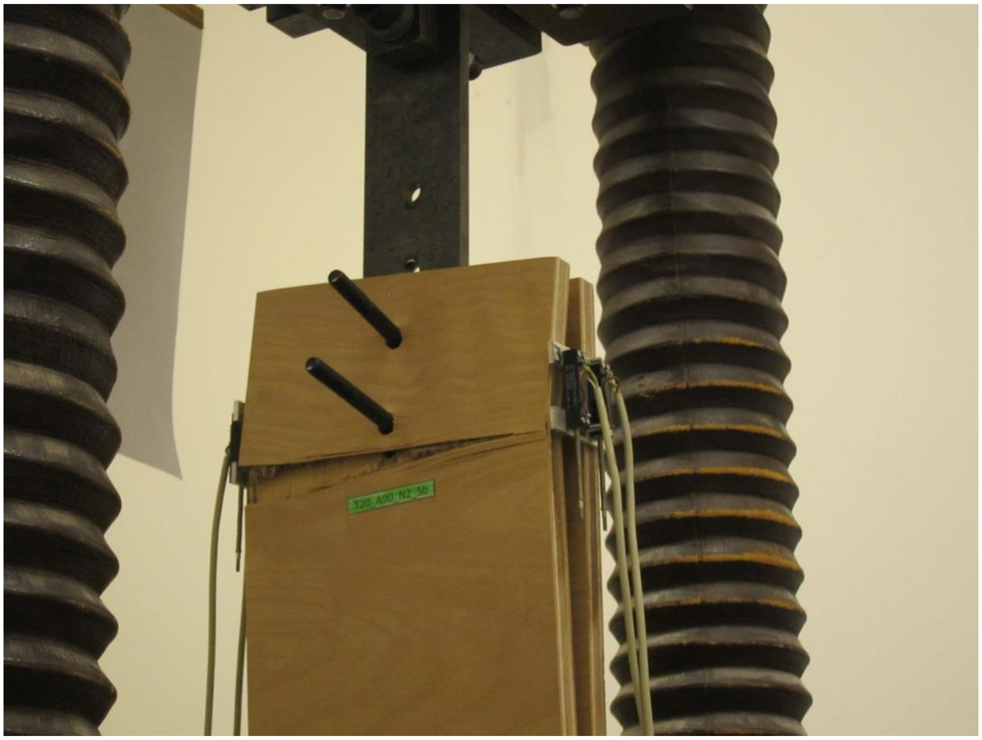
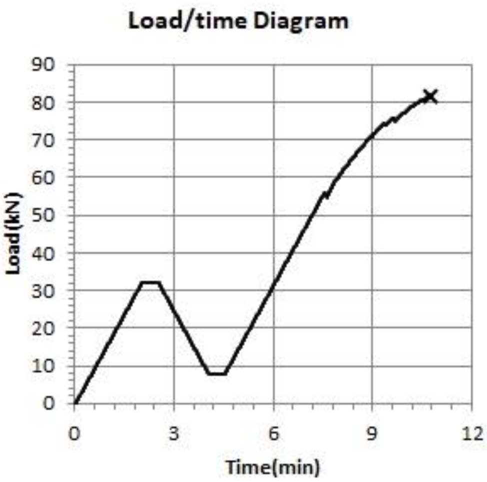


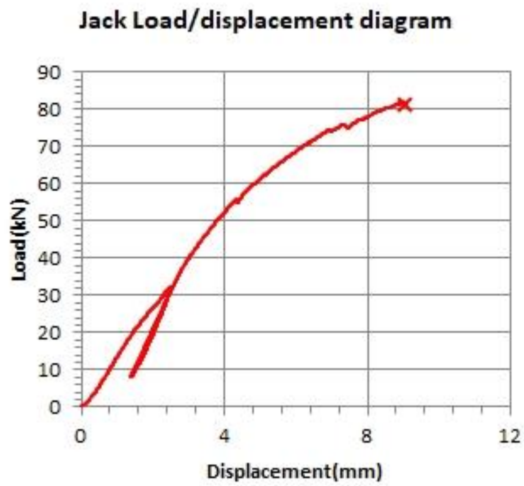
Figure 473 Perspective view nr1. After testing

Data:

T20_A90_N2_5	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	82,12	4,27	2,45	9,02	10,74
$F_{0,5}$	-	-	-	-	-
$F_{failure}$	81,21	4,36	2,46	9,08	10,78

Table 152 Results of specimen T20_A90_N2_5





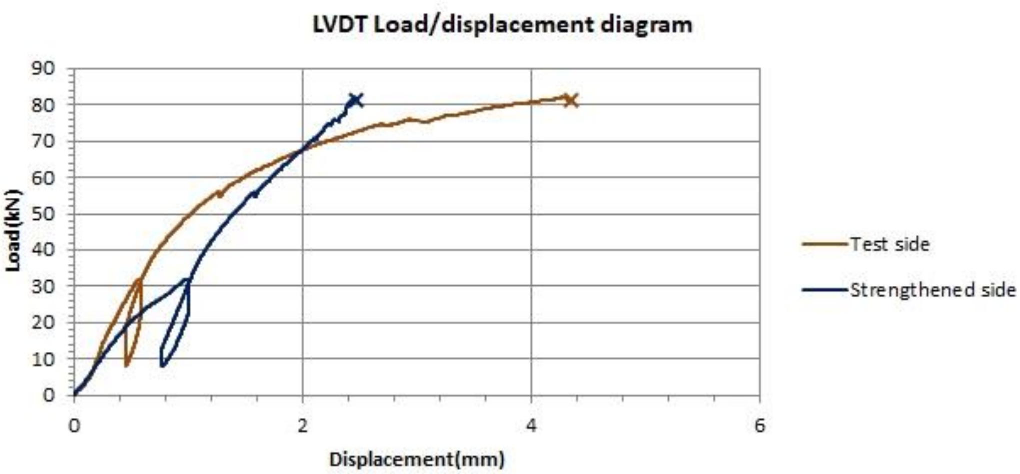


Figure 474 Graphical results of T20_A90_N2_5

13.13 T20_A90_N3

Before Testing(pictures test specimen T20_A90_N3_1 tensile failure):

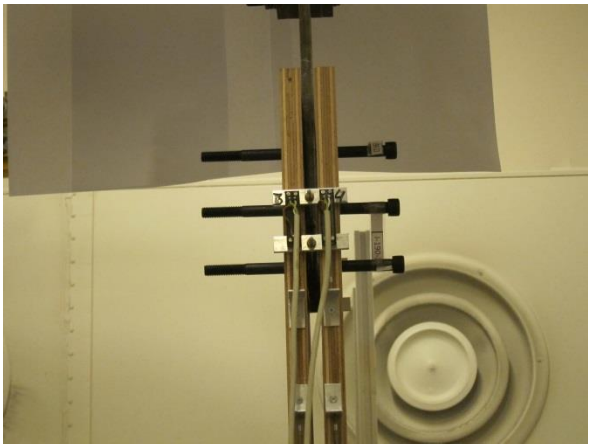


Figure 475 Front view

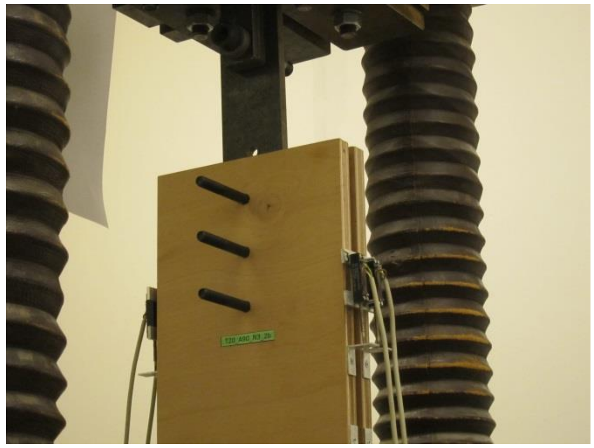


Figure 476 Perspective view nr. 1

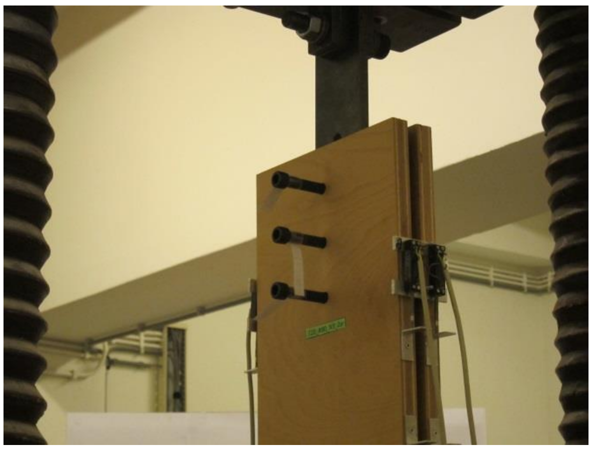


Figure 477 Perspective view nr 2

Figure 478 Overview material

Figure 479 Overview materials

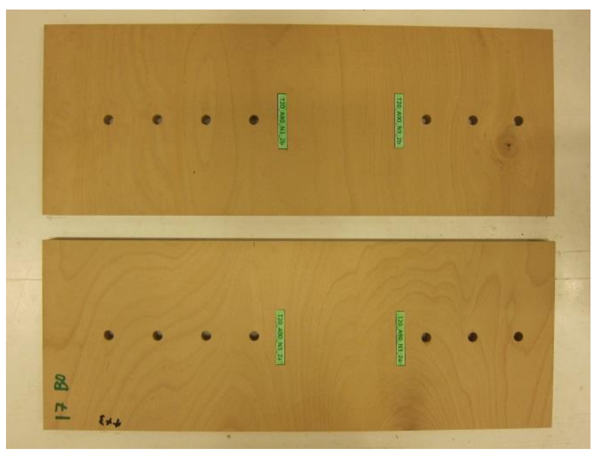


Figure 480 Overview materials

After testing

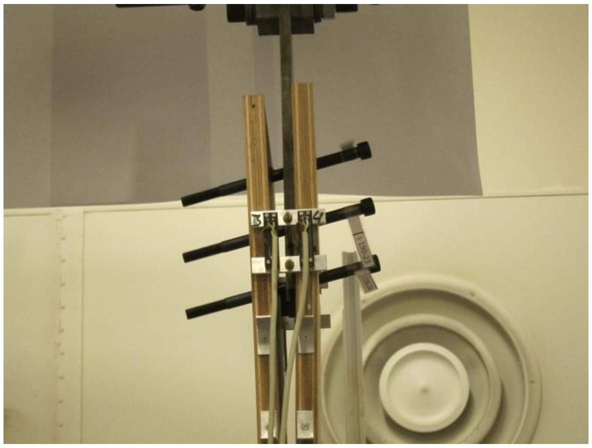


Figure 481 Front view

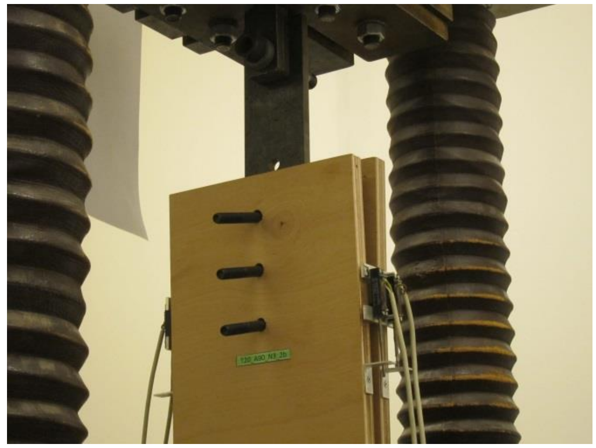


Figure 482 Perspective view nr. 1


Figure 483 Perspective view nr. 2

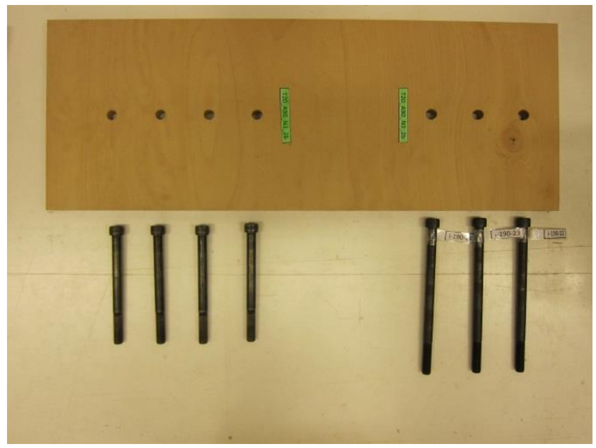


Figure 484 Overview materials

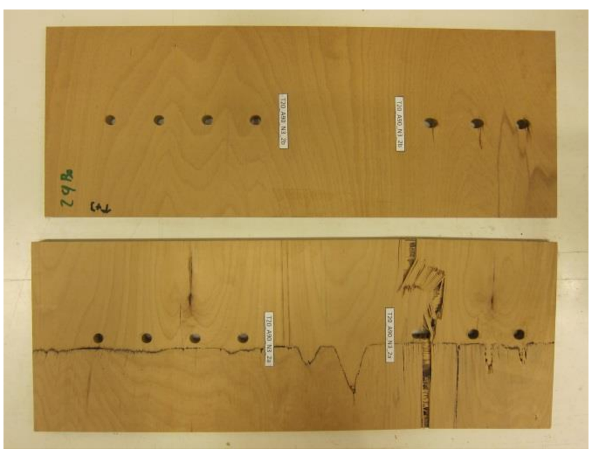


Figure 485 Overview materials

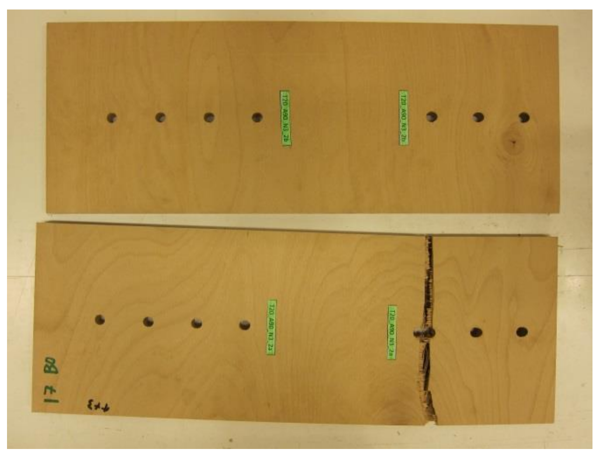


Figure 486 Overview materials

Figure 487 Closeup failure(Surface towards steel plate)

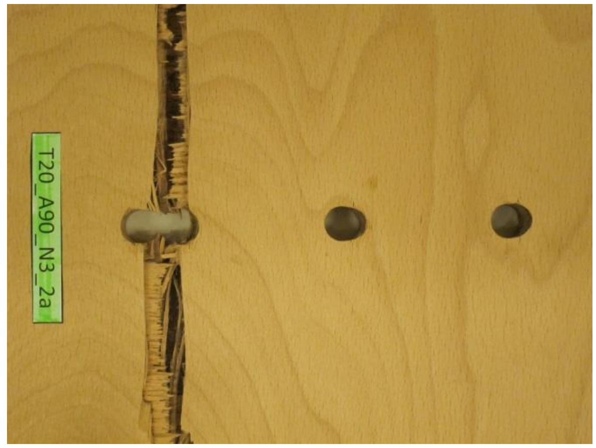


Figure 489 Closeup failure(Surface on the outside)

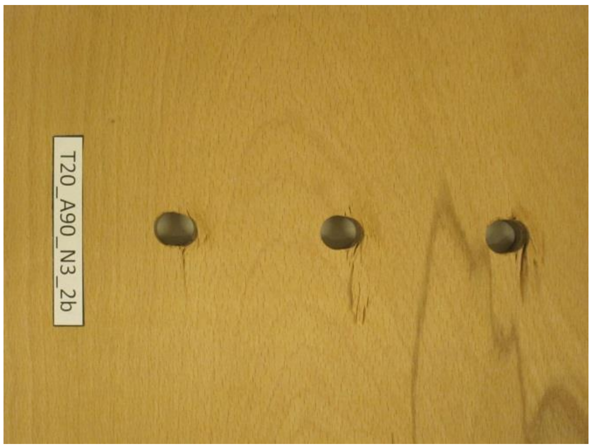


Figure 488 Closeup failure(Surface towards steel plate))

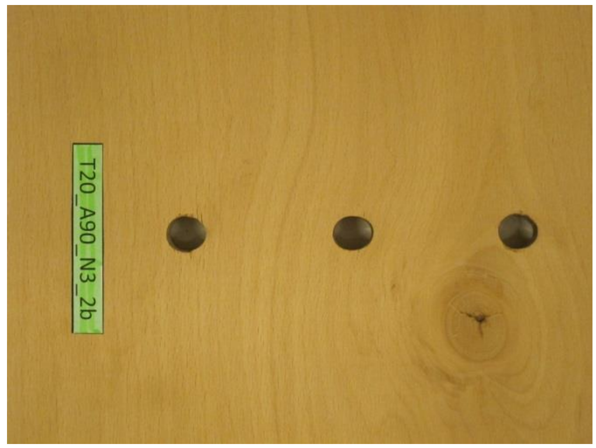


Figure 490 Closeup failure(Surface on the outside)

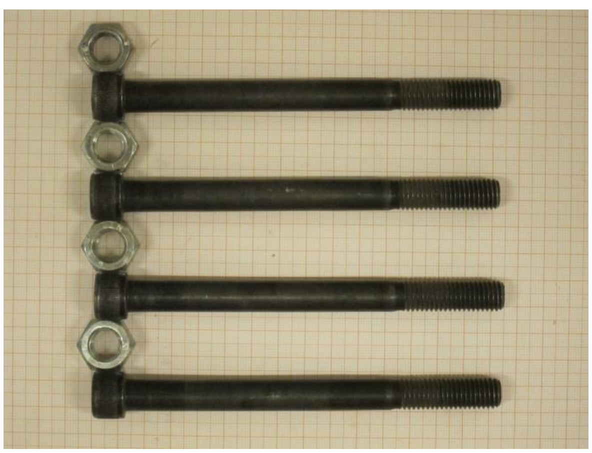


Figure 491 Dowels after testing strengthened side

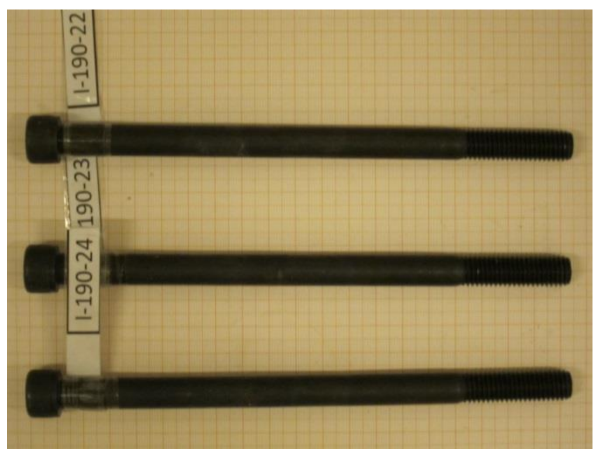


Figure 492 Dowels after testing test side

13.13.1 T20_A90_N3_1

Material coding:

Labels Timber	T20_A90_N3_1a	T20_A90_N3_1b		
Labels Steel Test side	I-190-19	I-190-20	I-190-21	
Labels Steel Strengthened. side	reused	reused	reused	reused

Table 153 Material coding T20_A90_N3_1

Log:

Material: *void in specimen b, discovered due to sawing for humidity determination*
F_{est}: *100kN*
Displacement controlled speed(1): *0.023mm/s*
Displacement controlled speed(2): *mm/s*

During testing: *as planned*

Cause of failure: *tension failure*

Additional remarks:

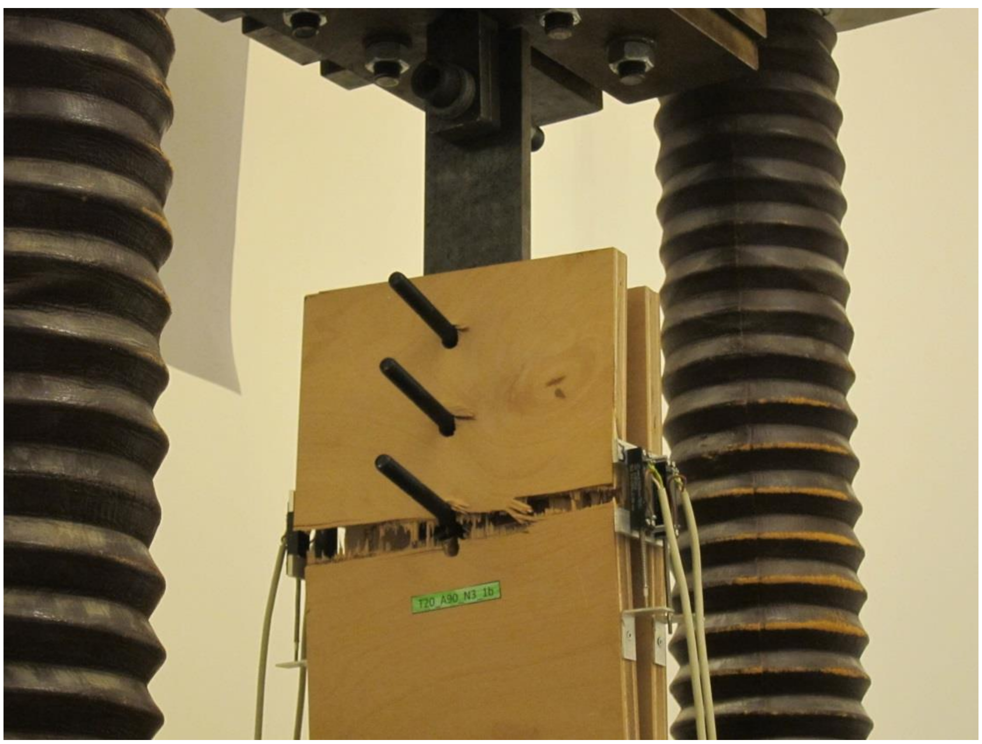
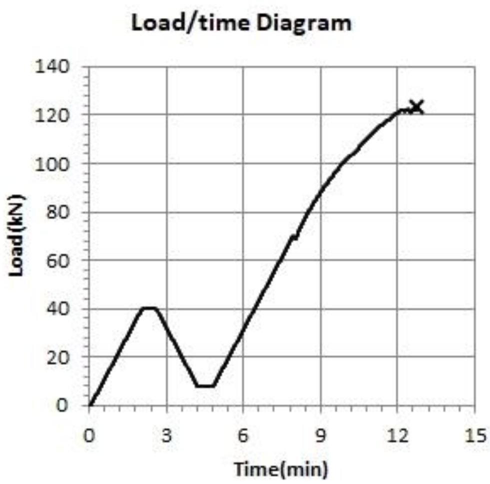


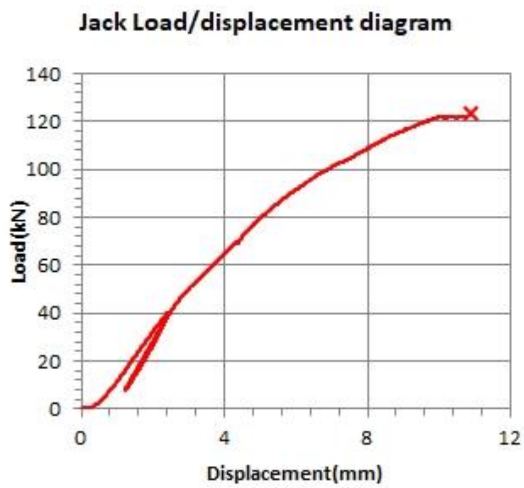
Figure 493 Perspective view nr1. After testing

Data:

T20_A90_N3_1	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	123,16	4,74	3,16	10,90	12,79
$F_{0,5}$	-	-	-	-	-
$F_{failure}$	122,98	4,76	3,17	10,90	12,80

Table 154 Results of specimen T20_A90_N3_1





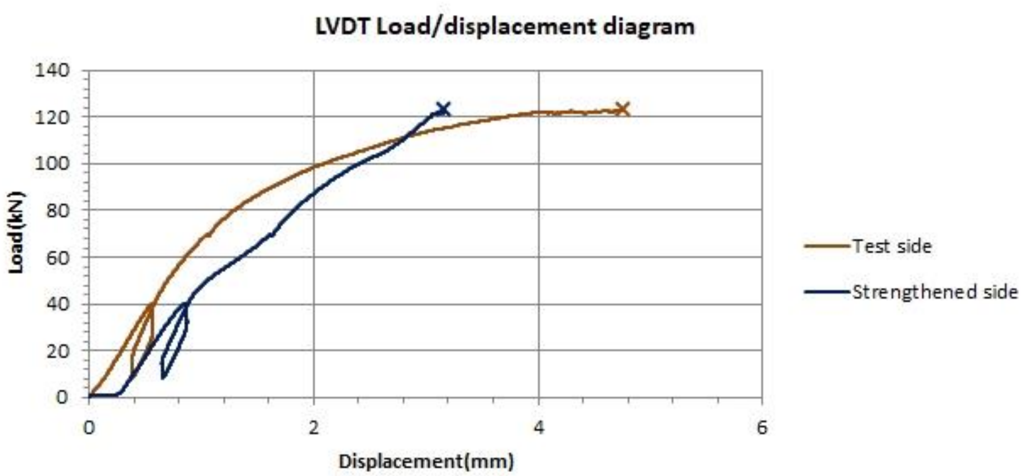


Figure 494 Graphical results of T20_A90_N3_1

13.13.2 T20_A90_N3_2

Material coding:

Labels Timber	T20_A90_N3_2a	T20_A90_N3_2b		
Labels Steel Test side	I-190-22	I-190-23	I-190-24	
Labels Steel Strengthened. side	reused	reused	reused	reused

Table 155 Material coding T20_A90_N3_2

Log:

Material: *clear specimen*

F_{est}: *120kN*
Displacement controlled speed(1): *0.03mm/s*
Displacement controlled speed(2): *mm/s*

During testing: *as planned*

Cause of failure: *tension failure*

Additional remarks:

Figure 495 Perspective view nr1. After testing

Data:

T20_A90_N3_2	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	112,73	3,98	2,96	9,64	10,06
$F_{0,5}$	-	-	-	-	-
$F_{failure}$	112,71	4,13	2,99	9,81	10,16

Table 156 Results of specimen T20_A90_N3_2

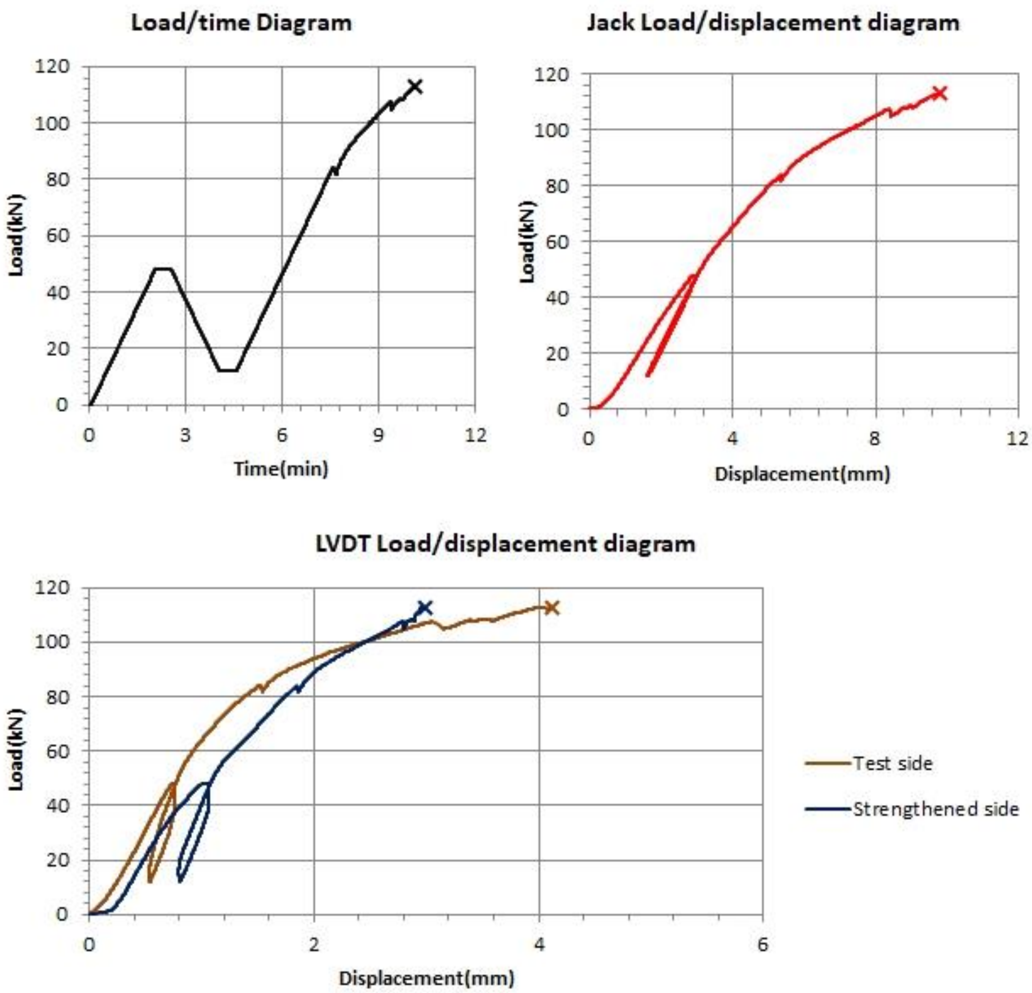


Figure 496 Graphical results of T20_A90_N3_2

13.13.3 T20_A90_N3_3S

Material coding:

Labels Timber	T20_A90_N3_3a	T20_A90_N3_3b		
Labels Steel Test side	I-140-26(re-used x1)	I-140-27(re-used x1)	I-140-28(re-used x1)	
Labels Steel Strengthened. side	reused	reused	reused	reused

Table 157 Material coding T20_A90_N3_3S

Log:

<u>Material</u>: *Top layer very thin gone in specimen a*

<u>F_{est}:</u> *120kN*
<u>Displacement controlled speed(1):</u> *0.03mm/s*
<u>Displacement controlled speed(2):</u> *mm/s*

<u>During testing</u>: *as planned*

<u>Cause of failure:</u> *tension failure*

<u>Additional remarks:</u> *dowels ordered were late had to use reuse dowels on test side. Also failure on strengthened side*

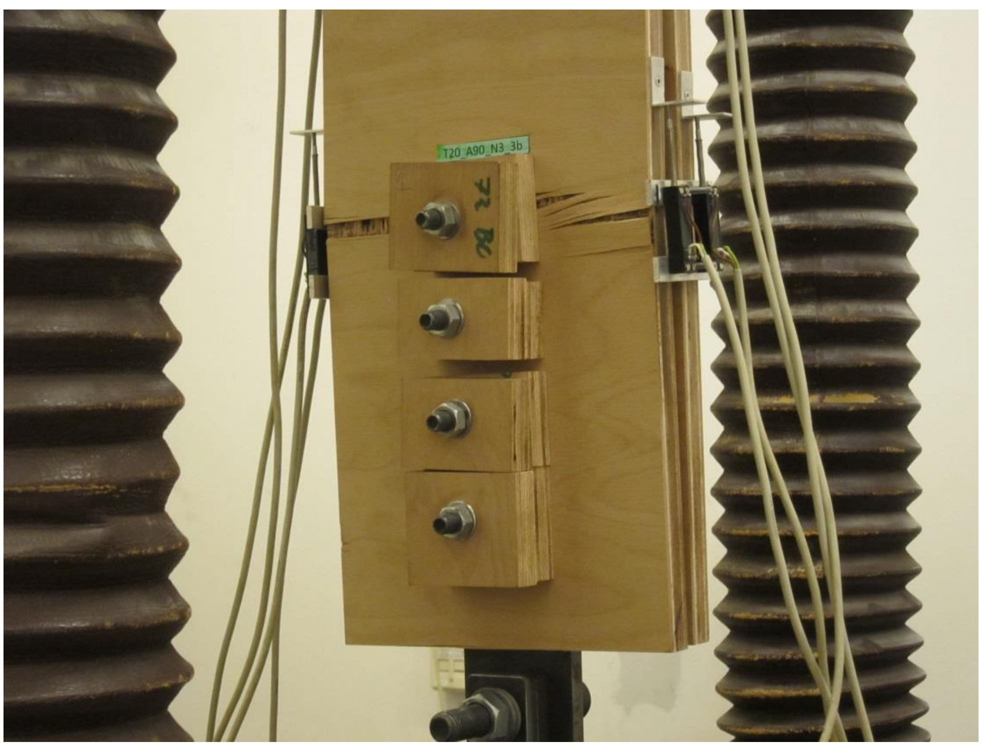


Figure 497 Perspective view nr1. After testing

Data:

T20_A90_N3_3S	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	115,70	3,31	2,72	8,85	9,65
$F_{0,5}$	-	-	-	-	-
$F_{failure}$	115,63	3,32	2,72	8,86	9,66

Table 158 Results of specimen T20_A90_N3_3S

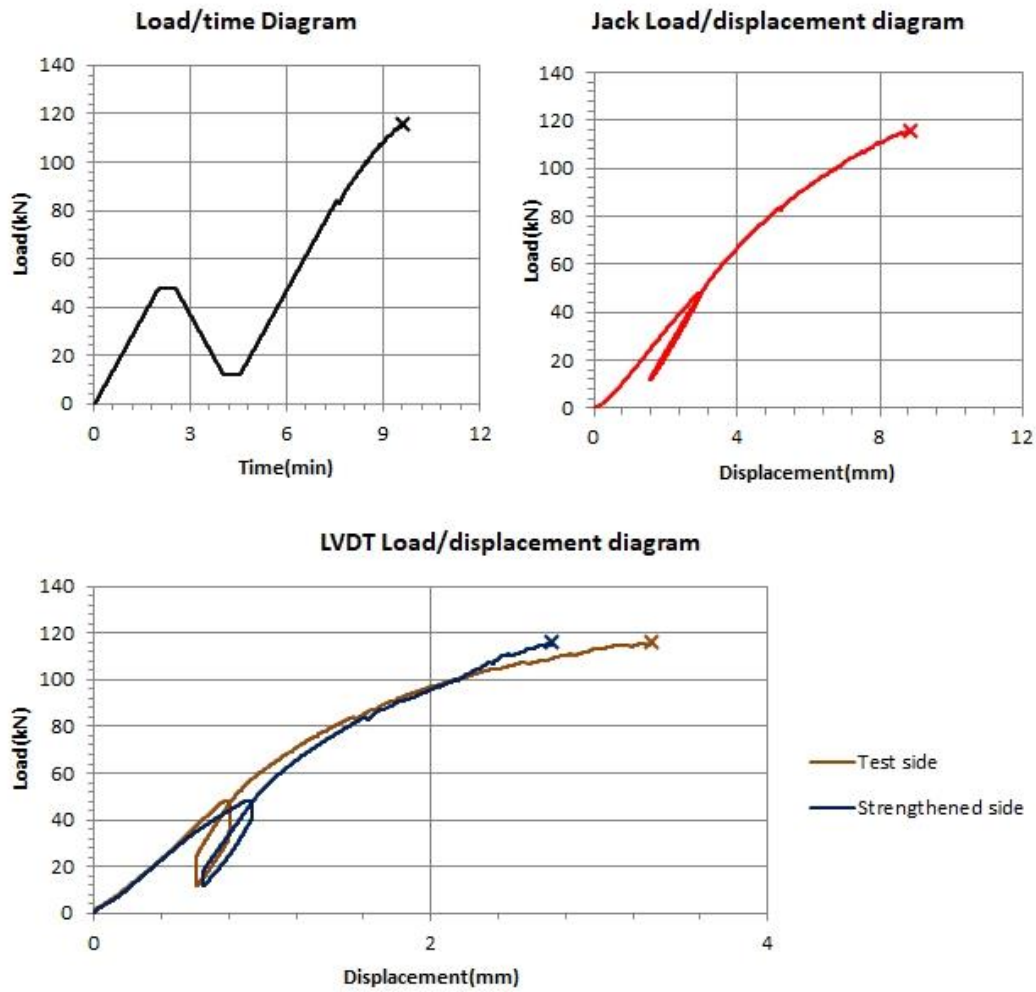


Figure 498 Graphical results of T20_A90_N3_3S

13.13.4 T20_A90_N3_4S

Material coding:

Labels Timber	T20_A90_N3_4a	T20_A90_N3_4b		
Labels Steel Test side	I-140-27(re-used x2)	I-140-29(re-used x1)	I-140-33(re-used x1)	
Labels Steel Strengthened. side	reused	reused	reused	reused

Table 159 Material coding T20_A90_N3_4S

Log:

<u>Material</u>: *clear specimen*

<u>F_{est}:</u> *120kN*
<u>Displacement controlled speed(1):</u> *0.03mm/s*
<u>Displacement controlled speed(2):</u> *mm/s*

<u>During testing</u>: *as planned*

<u>Cause of failure:</u> *tension failure*

<u>Additional remarks:</u>

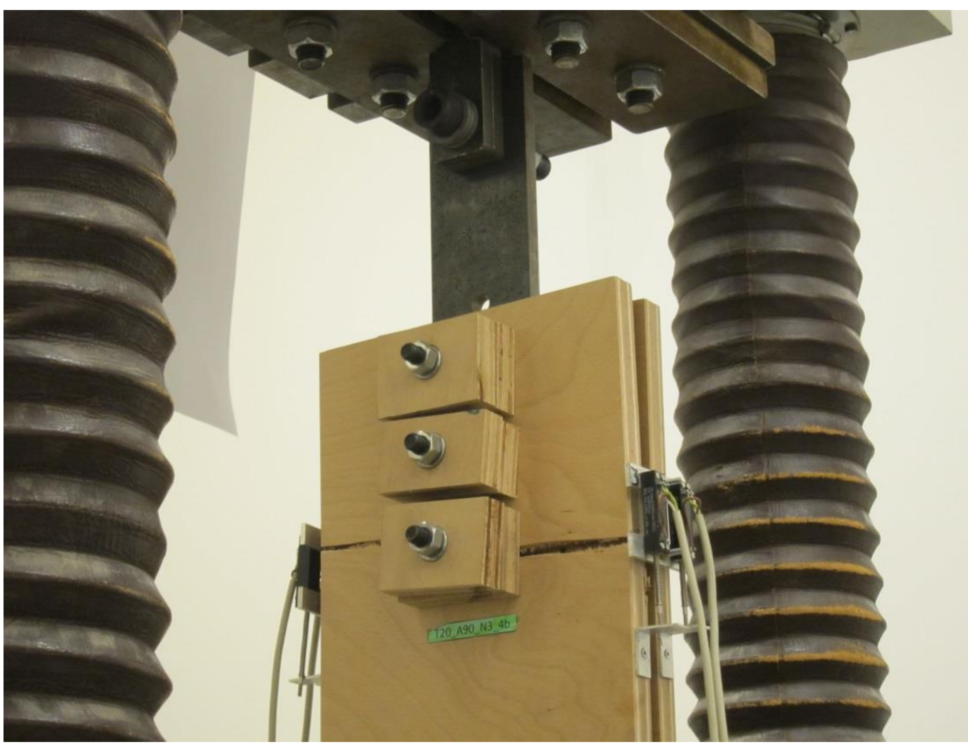


Figure 499 Perspective view nr1. After testing

Data:

T20_A90_N3_4S	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	118,05	3,27	3,07	9,22	9,93
$F_{0,5}$	-	-	-	-	-
$F_{failure}$	116,58	3,36	3,12	9,28	9,97

Table 160 Results of specimen T20_A90_N3_4S

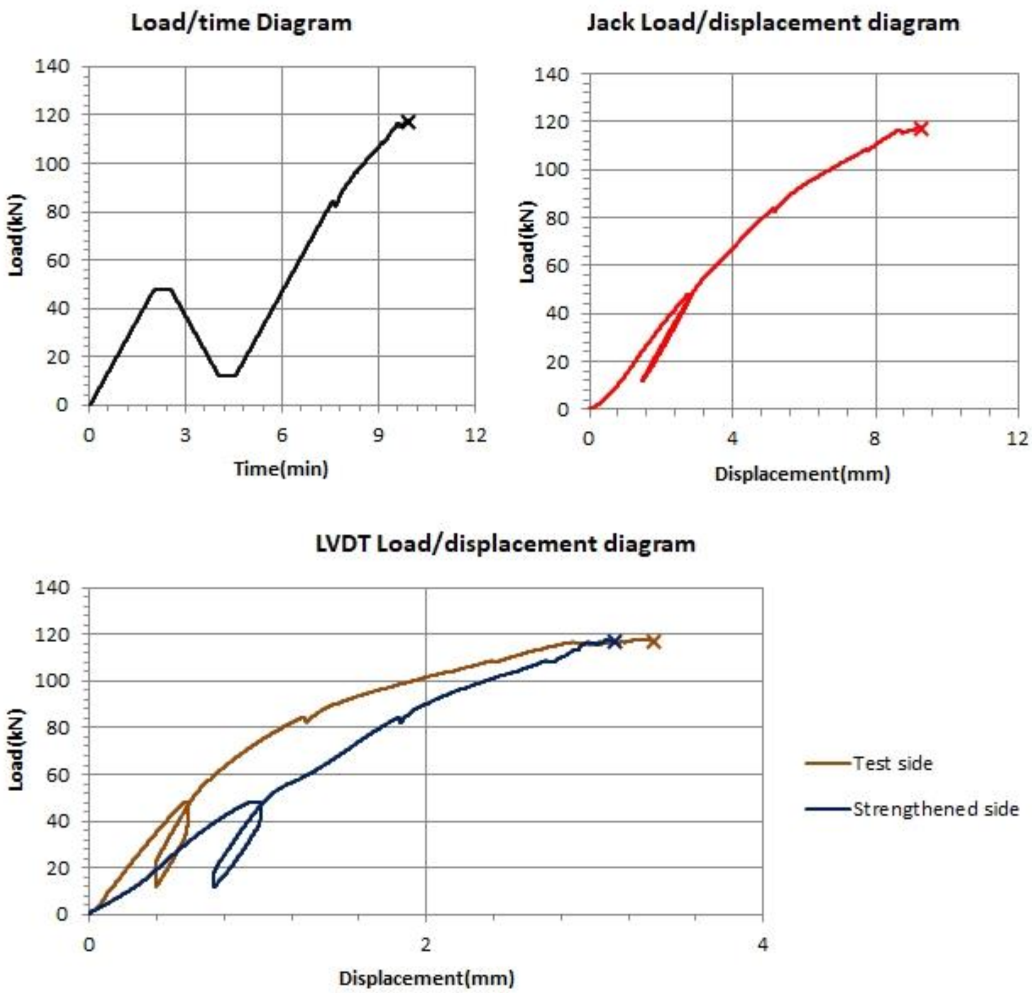


Figure 500 Graphical results of T20_A90_N3_4S

13.13.5 T20_A90_N3_5S

Material coding:

Labels Timber	T20_A90_N3_5a	T20_A90_N3_5b		
Labels Steel Test side	I-140-27(re-used x3)	I-140-29(re-used x2)	I-140-33(re-used x2)	
Labels Steel Strengthened. side	reused	reused	reused	reused

Table 161 Material coding T20_A90_N3_5S

Log:

<u>Material</u>: *clear specimen*

<u>F_{est}:</u> *120kN*
<u>Displacement controlled speed(1):</u> *0.03mm/s*
<u>Displacement controlled speed(2):</u> *mm/s*

<u>During testing</u>: *as planned*

<u>Cause of failure:</u> *tension failure*

<u>Additional remarks:</u>

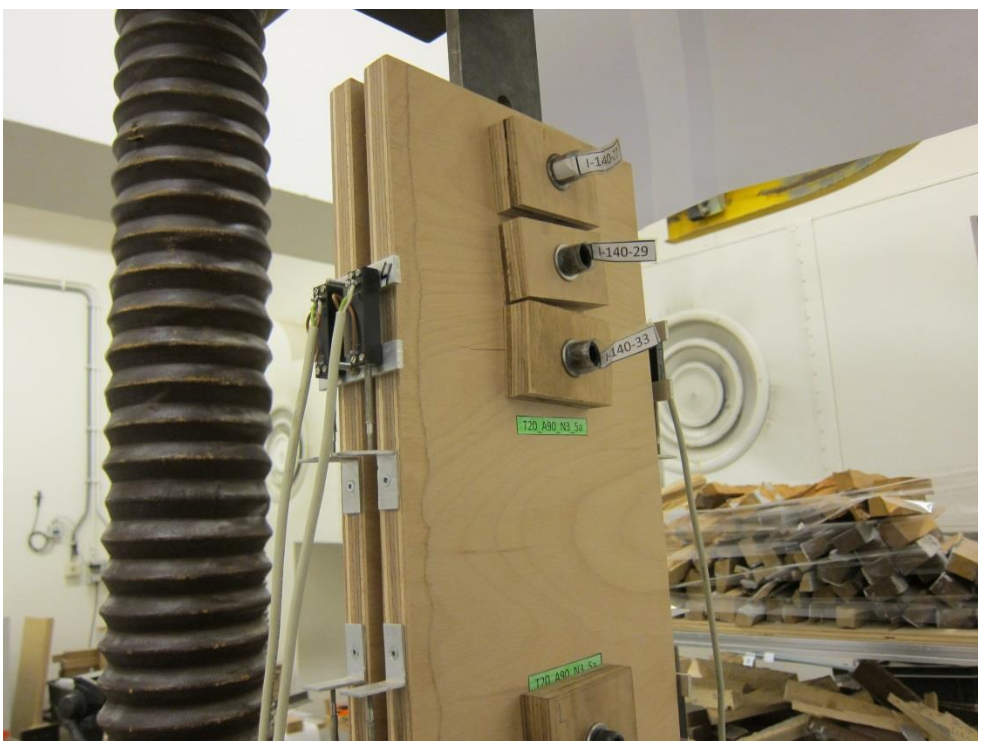


Figure 501 random perspective After testing to show crack

Data:

T20_A90_N3_5S	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	125,53	4,02	3,22	10,31	10,30
$F_{0,5}$	-	-	-	-	-
$F_{failure}$	124,34	4,10	3,25	10,35	10,32

Table 162 Results of specimen T20_A90_N3_5S

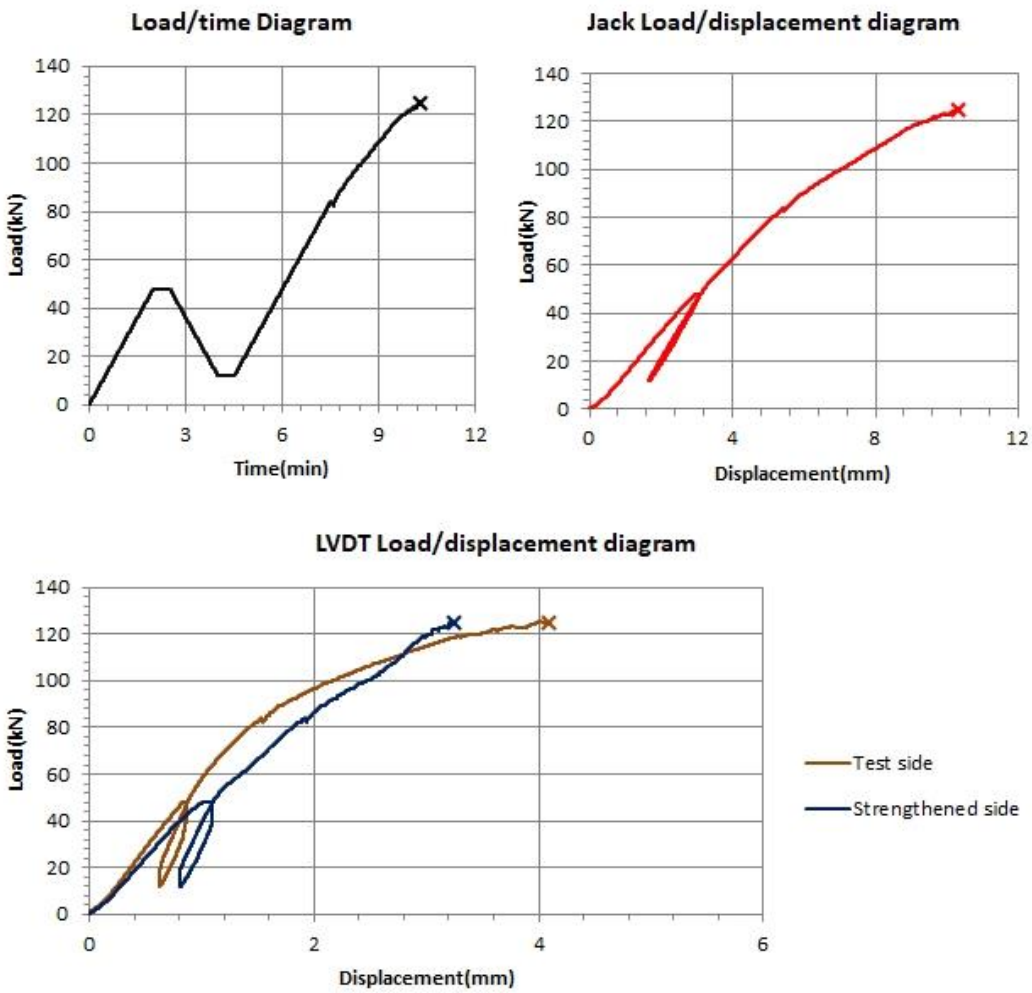


Figure 502 Graphical results of T20_A90_N3_5S

13.14 T40_A0_N1

Before Testing(pictures test specimen T40_A0_N1_1 embedment/FM II failure):

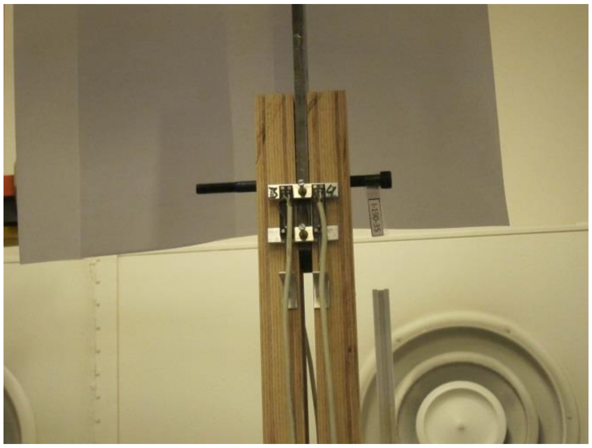


Figure 503 Front view

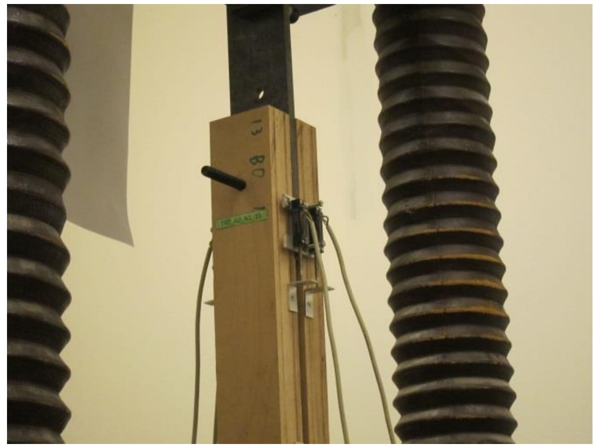


Figure 504 Perspective view nr. 1

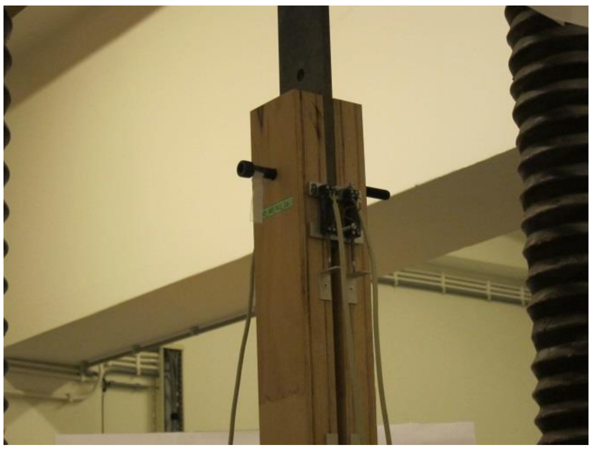


Figure 505 Perspective view nr 2

Figure 506 Overview materials

Figure 507 Overview materials

After testing

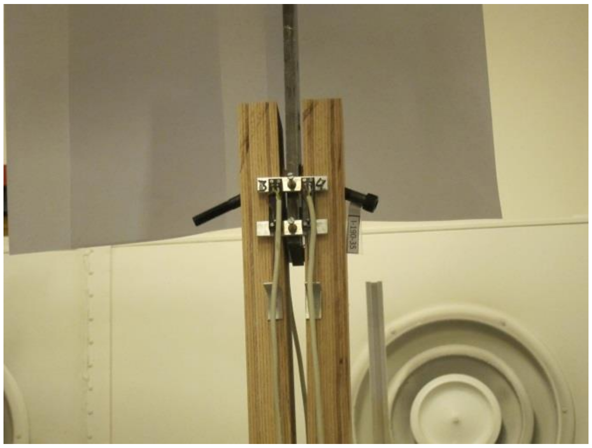


Figure 508 Front view

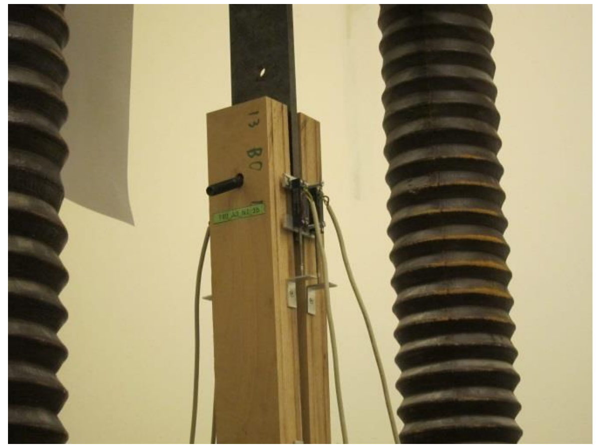


Figure 509 Perspective view nr. 1

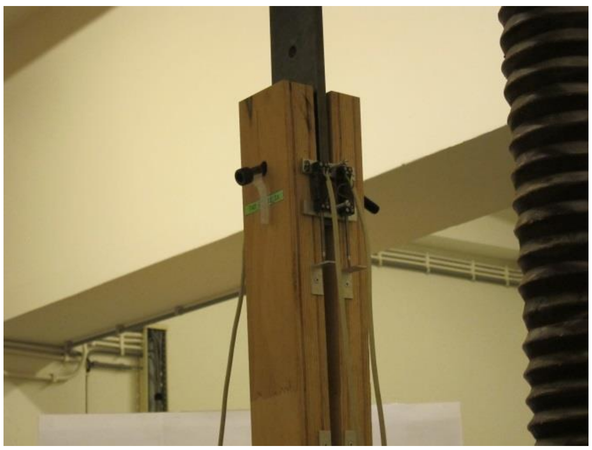


Figure 510 perspective view nr 2

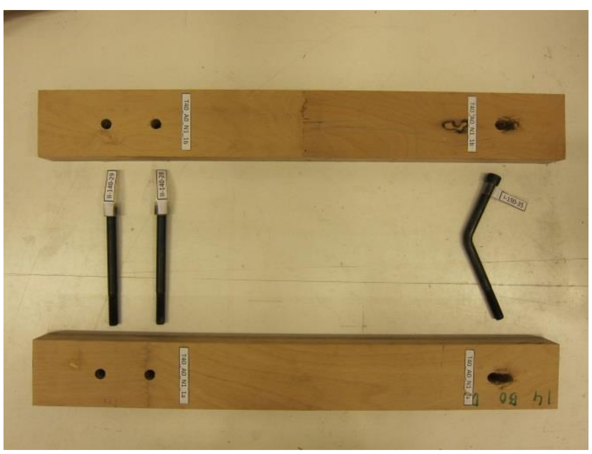


Figure 511 Overview materials

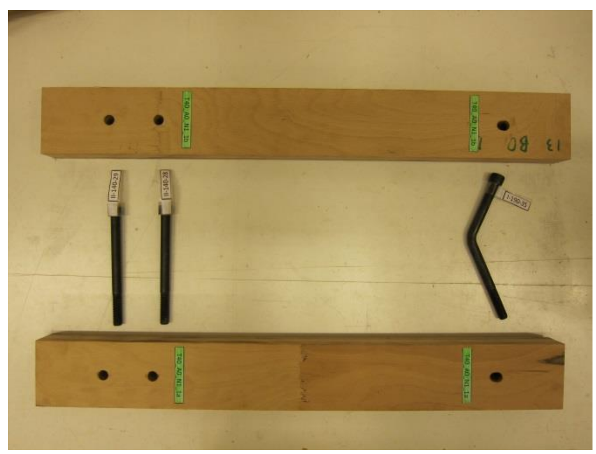


Figure 512 Overview materials

Figure 513 Closeup failure(Surface towards steel plate)

Figure 515 Closeup failure(Surface on the outside)

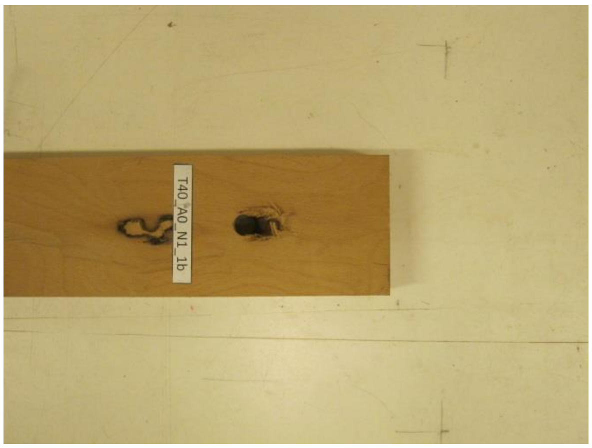


Figure 514 Closeup failure(Surface towards steel plate)

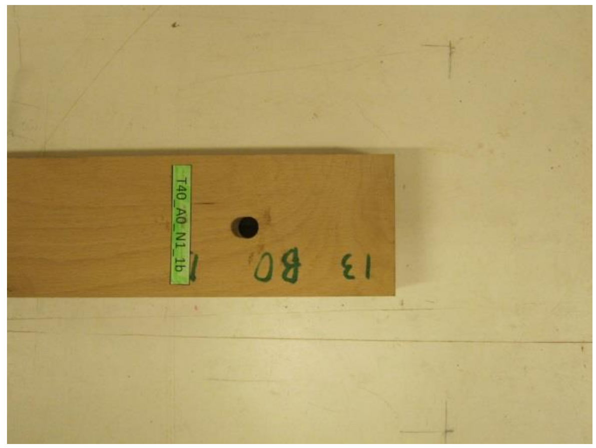


Figure 516 Closeup failure(Surface on the outside)

Figure 517 Dowels after testing strengthened side

Figure 518 dowels after testing test side

13.14.1 T40_A0_N1_1

Material coding:

Labels Timber	T40_A0_N1_1a	T40_A0_N1_1b
Labels Steel Test side	I-190-35	
Labels Steel Strengthened. side	II-140-28	II-140-29

Table 163 Material coding T40_A0_N1_1

Log:

Material: *clear specimen*

F_{est}: *60kN*
Displacement controlled speed(1): *0.02mm/s*
Displacement controlled speed(2): *mm/s*

During testing: *as planned*

Cause of failure: *embedment failure(mode II)*

Additional remarks:

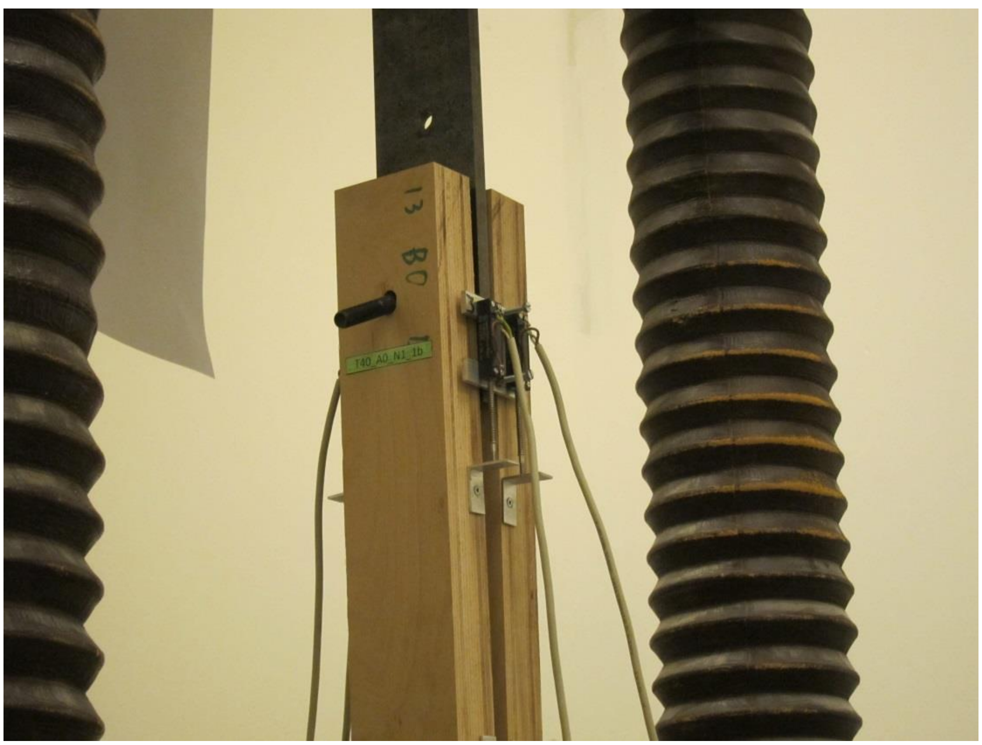


Figure 519 Perspective view nr1. After testing

Data:

T40_A0_N1_1	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	63,72	17,30	0,94	19,76	21,77
$F_{0,5}$	53,91	5,00	0,77	7,07	11,19
$F_{failure}$	-	-	-	-	-

Table 164 Results of specimen T40_A0_N1_1

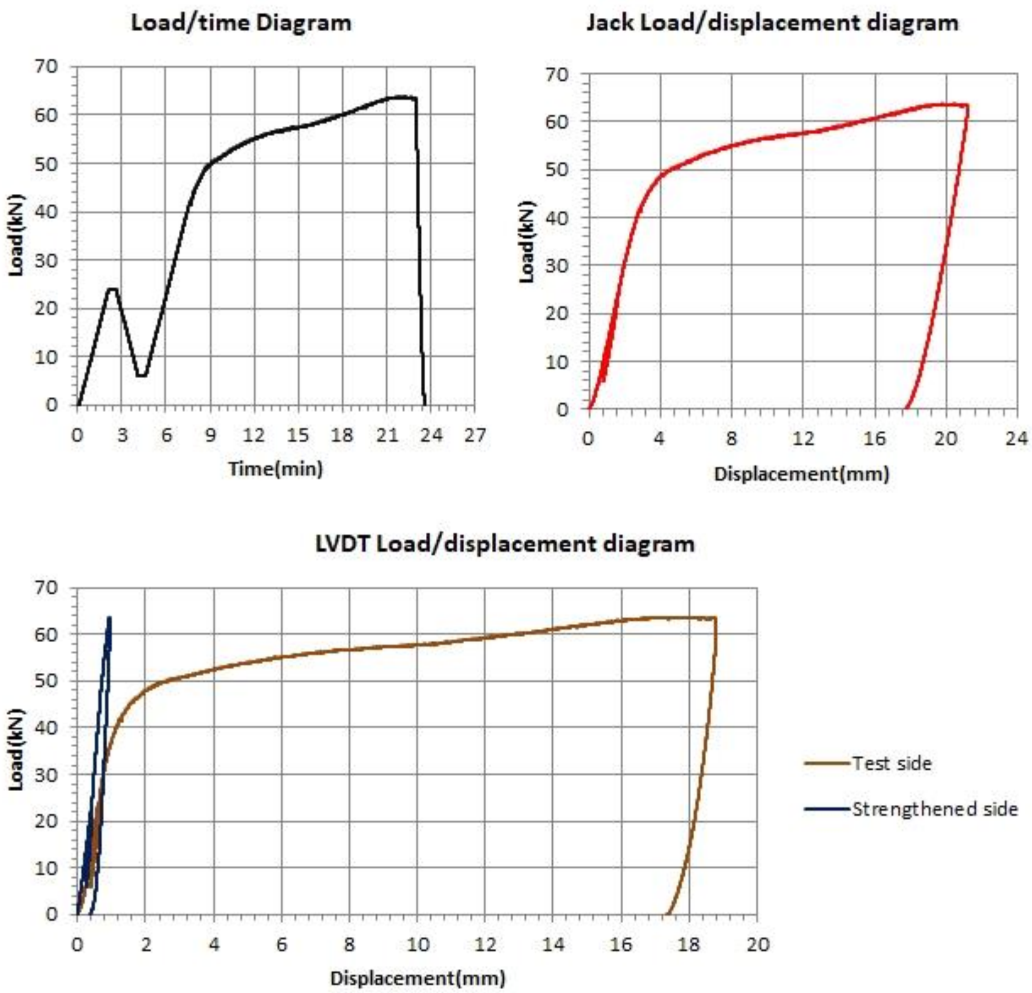


Figure 520 Graphical results of T40_A0_N1_1

13.14.2 T40_A0_N1_2

Material coding:

Labels Timber	T40_A0_N1_2a	T40_A0_N1_2b
Labels Steel Test side	I-190-36	
Labels Steel Strengthened. side	II-140-30	II-140-31

Table 165 Material coding T40_A0_N1_2

Log:

Material: *some knots but nothing extraordinary*

F_{est}: *65kN*

Displacement controlled speed(1): *0.03mm/s*

Displacement controlled speed(2): *mm/s*

During testing: *as planned*

Cause of failure: *embedment failure*

Additional remarks:

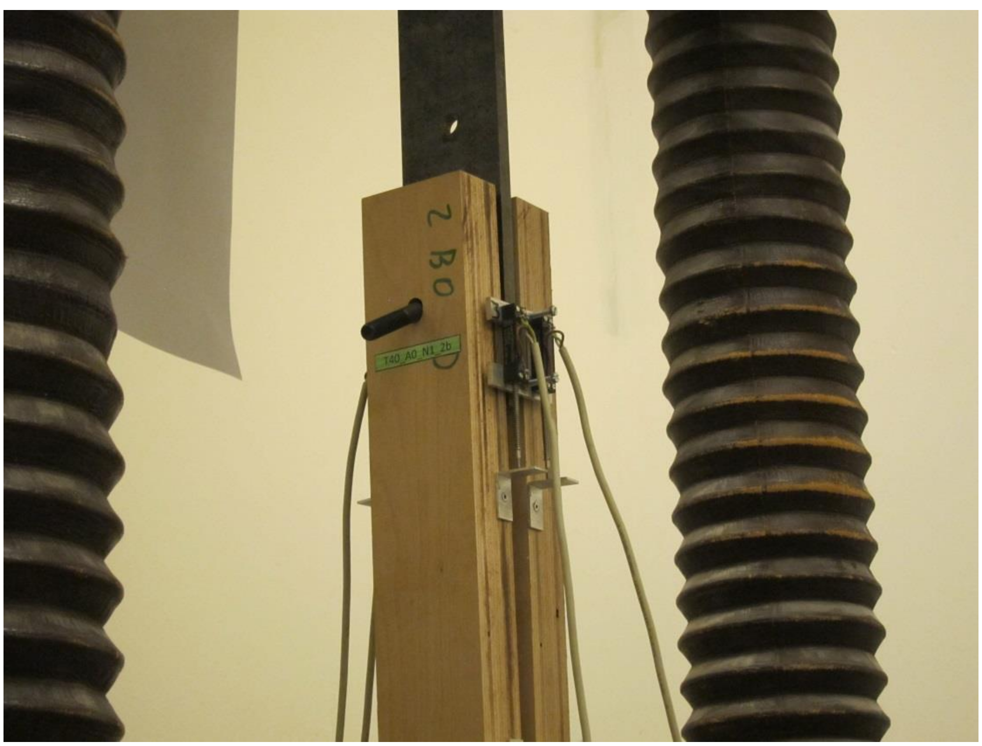
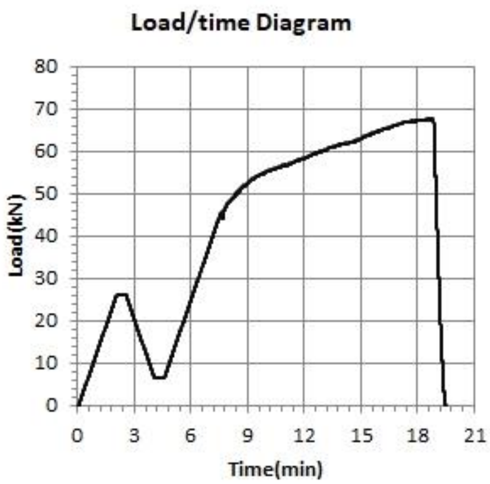


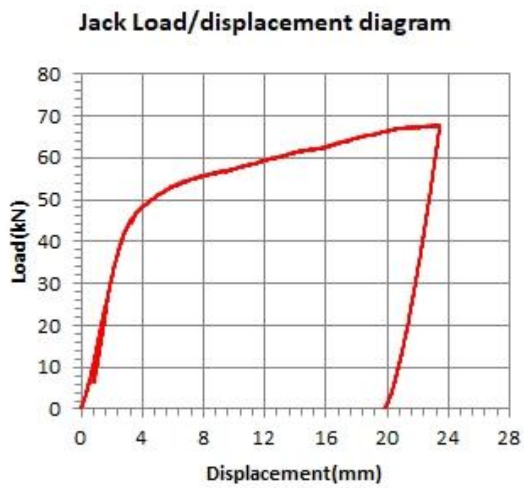
Figure 521 Perspective view nr1. After testing

Data:

T40_A0_N1_2	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	67,73	20,50	1,07	23,16	18,70
$F_{0,5}$	54,77	5,00	0,86	7,14	9,80
$F_{failure}$	-	-	-	-	-

Table 166 Results of specimen T40_A0_N1_2





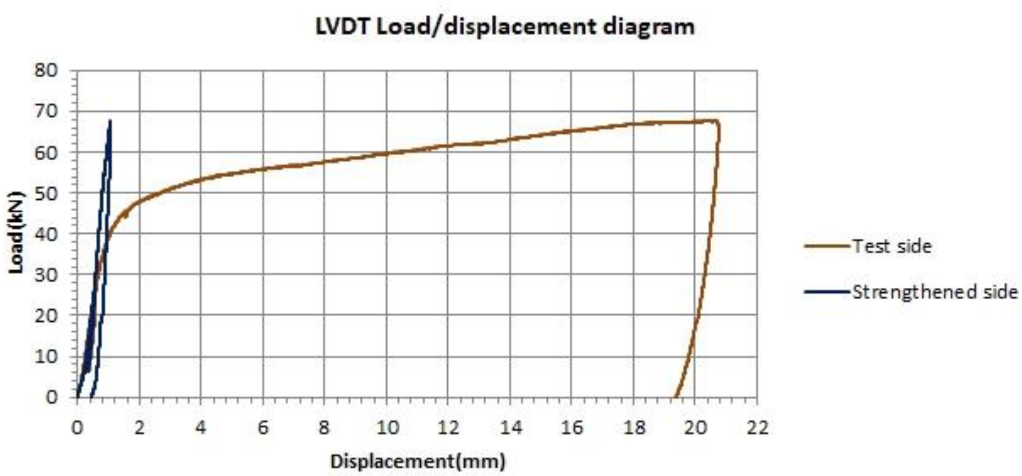


Figure 522 Graphical results of T40_A0_N1_2

13.15 T40_A0_N2

***Before Testing*(pictures test specimen T40_A0_N2_1 embedment/FM II failure):**

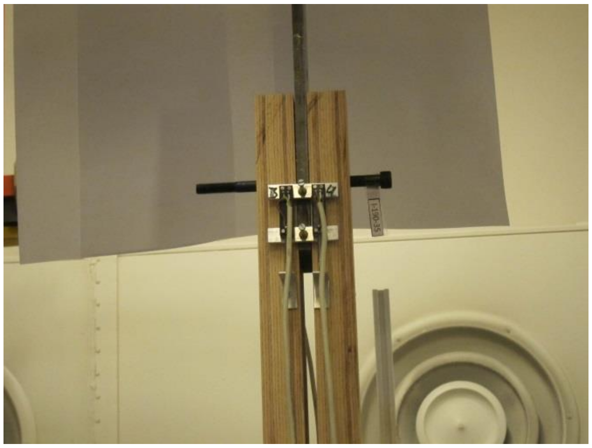


Figure 523 Front view

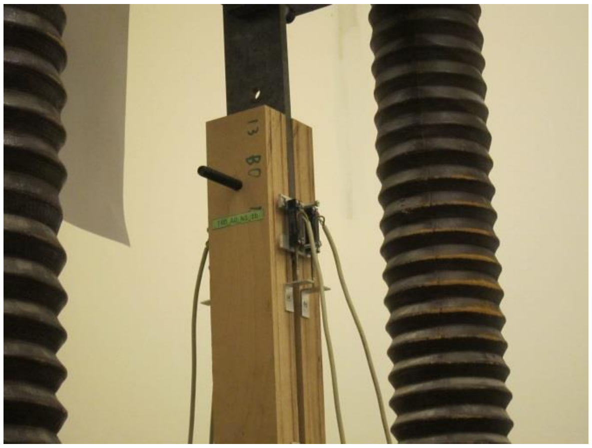


Figure 524 Perspective view nr. 1

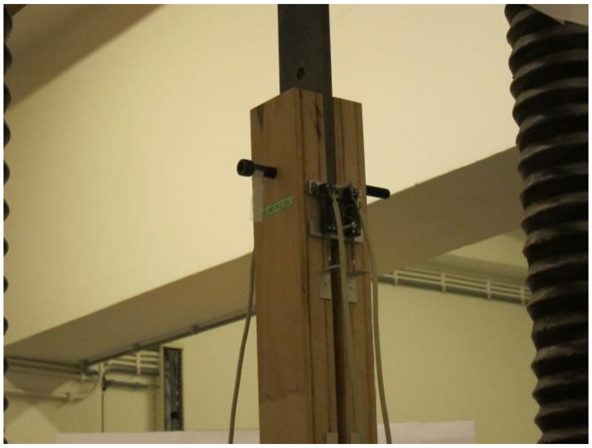


Figure 525 Perspective view nr 2

Figure 526 Overview materials

Figure 527 Overview materials

After testing

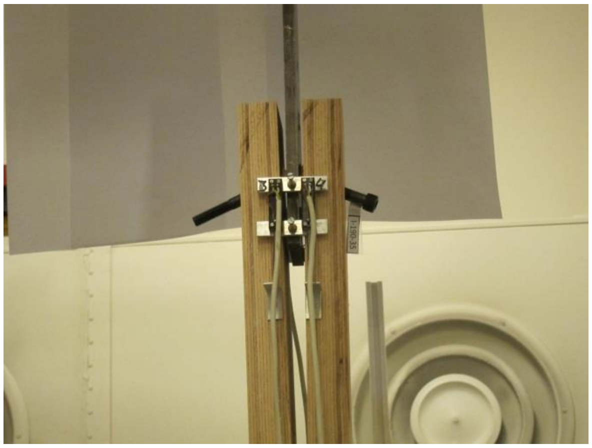


Figure 528 Front view

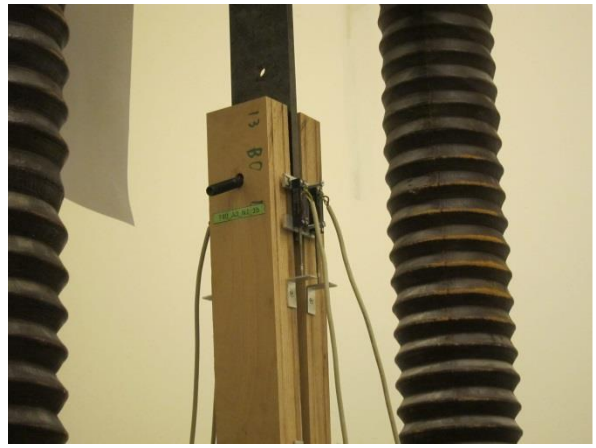


Figure 529 Perspective view nr. 1

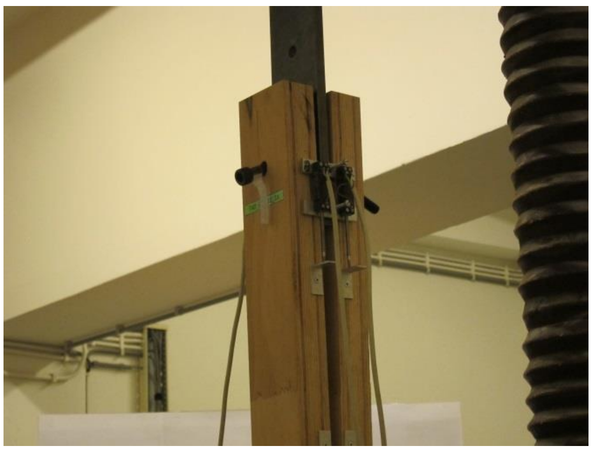


Figure 530 perspective view nr 2

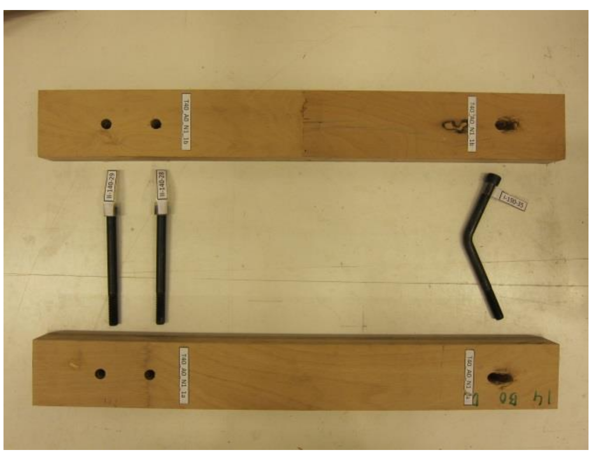


Figure 531 Overview materials

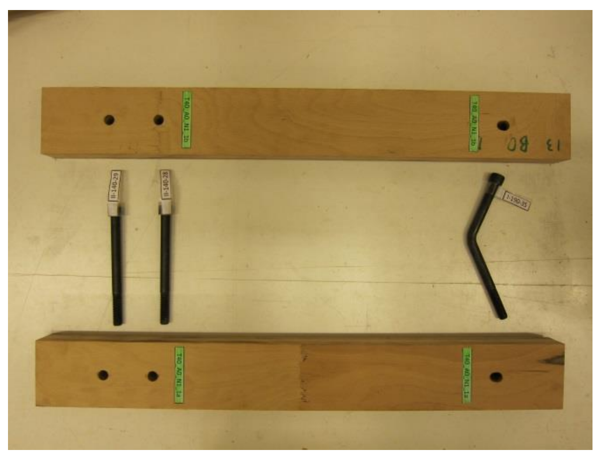


Figure 532 Overview materials

Figure 533 Closeup failure(Surface towards steel plate)

Figure 535 Closeup failure(Surface on the outside)

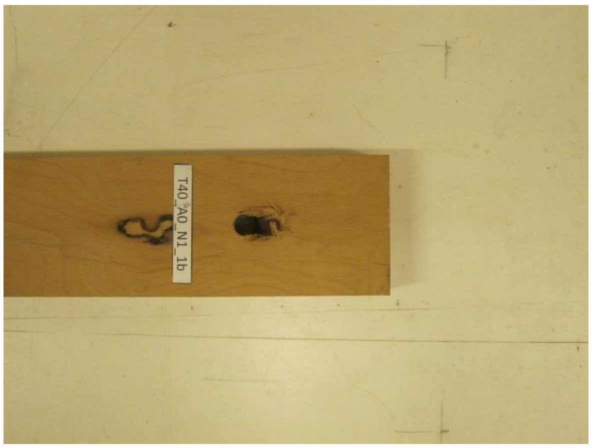


Figure 534 Closeup failure(Surface towards steel plate)

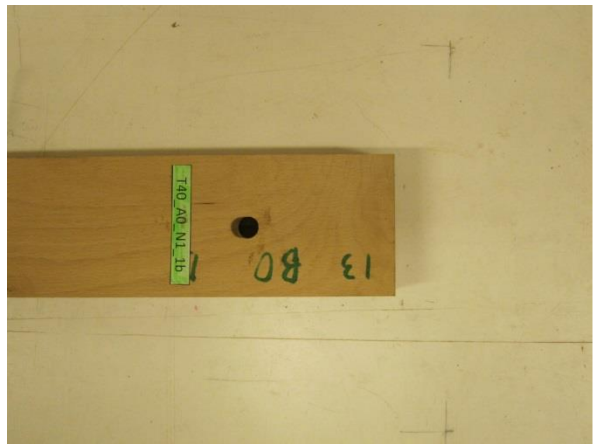


Figure 536 Closeup failure(Surface on the outside)

Figure 537 Dowels after testing strengthened side

Figure 538 dowels after testing test side

13.15.1 T40_A0_N2_1

Material coding:

Labels Timber	T40_A90_N2_1a	T40_A90_N2_1b	
Labels Steel Test side	I-190-37	I-190-38	
Labels Steel Strengthened. side	II-140-32	II-140-33	II-140-34

Table 167 Material coding T40_A0_N2_1

Log:

Material: *clear specimen*

F_{est}: *130kN*
Displacement controlled speed(1): *0.036mm/s*
Displacement controlled speed(2): *mm/s*

During testing: *as planned*

Cause of failure:

Additional remarks: *lot of cracking was heard during testing at the same moment of strength dropping. Turned out to be shearing of the top 3 layers*

Figure 539 Perspective view nr1. After testing

Data:

T40_A0_N2_1	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	112,21	20,52	1,43	24,46	16,76
$F_{0,5}$	106,81	5,00	1,26	8,67	9,45
$F_{failure}$	-	-	-	-	-

Table 168 Results of specimen T40_A0_N2_1

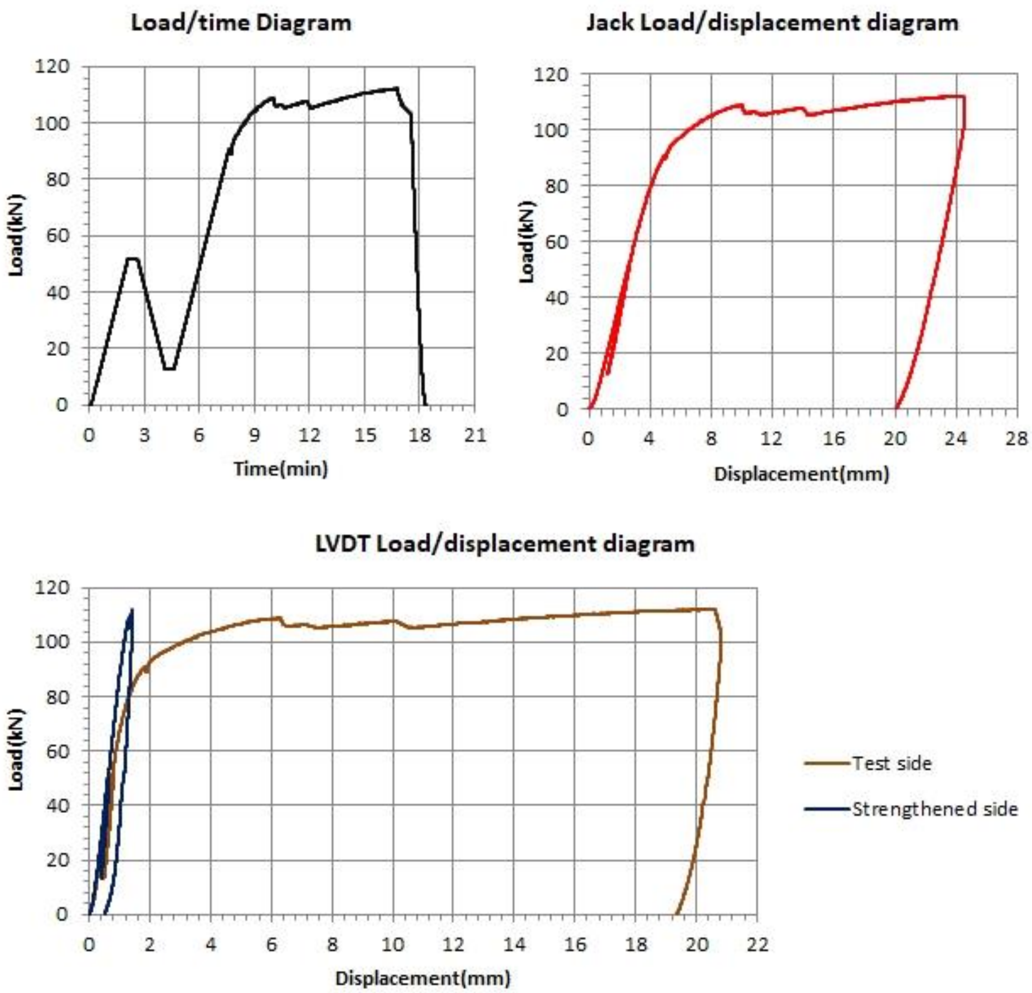


Figure 540 Graphical results of T40_A0_N2_1

13.15.2 T40_A0_N2_2

Material coding:

Labels Timber	T40_A90_N2_1a	T40_A90_N2_1b	
Labels Steel Test side	I-190-39	I-190-40	
Labels Steel Strengthened. side	II-140-35	II-140-36	II-140-37

Table 169 Material coding T40_A0_N2_2

Log:

Material: *clear specimen*

F_{est}: *130kN*
Displacement controlled speed(1): *0.04mm/s*
Displacement controlled speed(2): *mm/s*

During testing: *as planned*

Cause of failure: *embedment failure*

Additional remarks: expected strength was a bit higher to curve out better

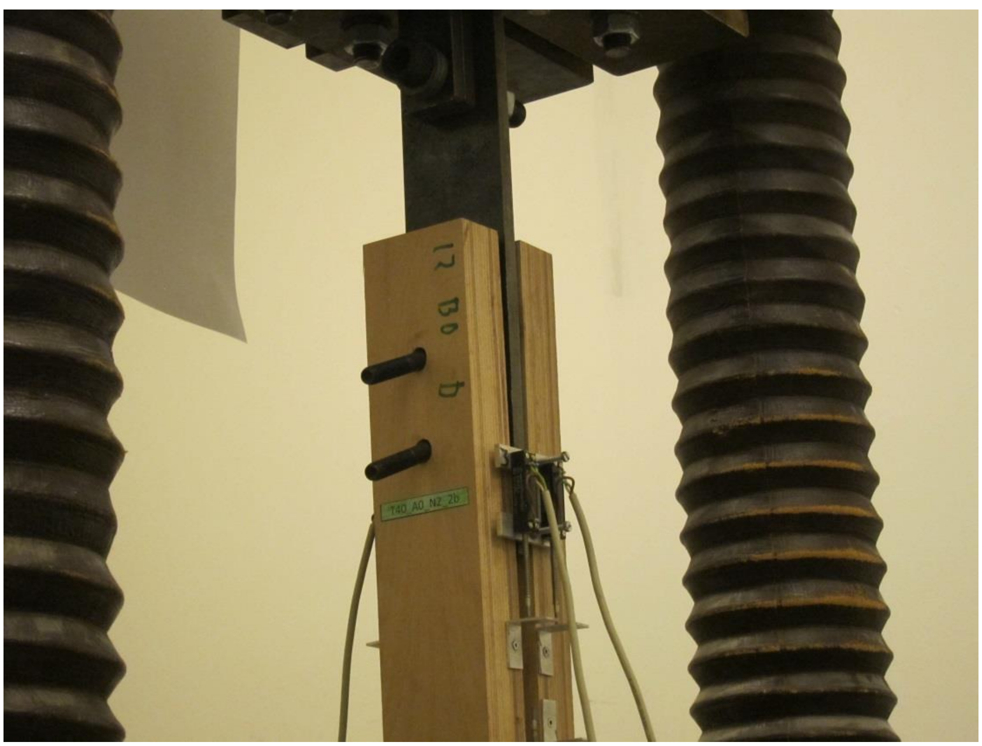


Figure 541 Perspective view nr1. After testing

Data:

T40_A0_N2_2	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	114,21	16,07	1,31	20,01	13,99
$F_{0,5}$	101,62	5,00	1,09	8,42	9,16
$F_{failure}$	-	-	-	-	-

Table 170 Results of specimen T40_A0_N2_2

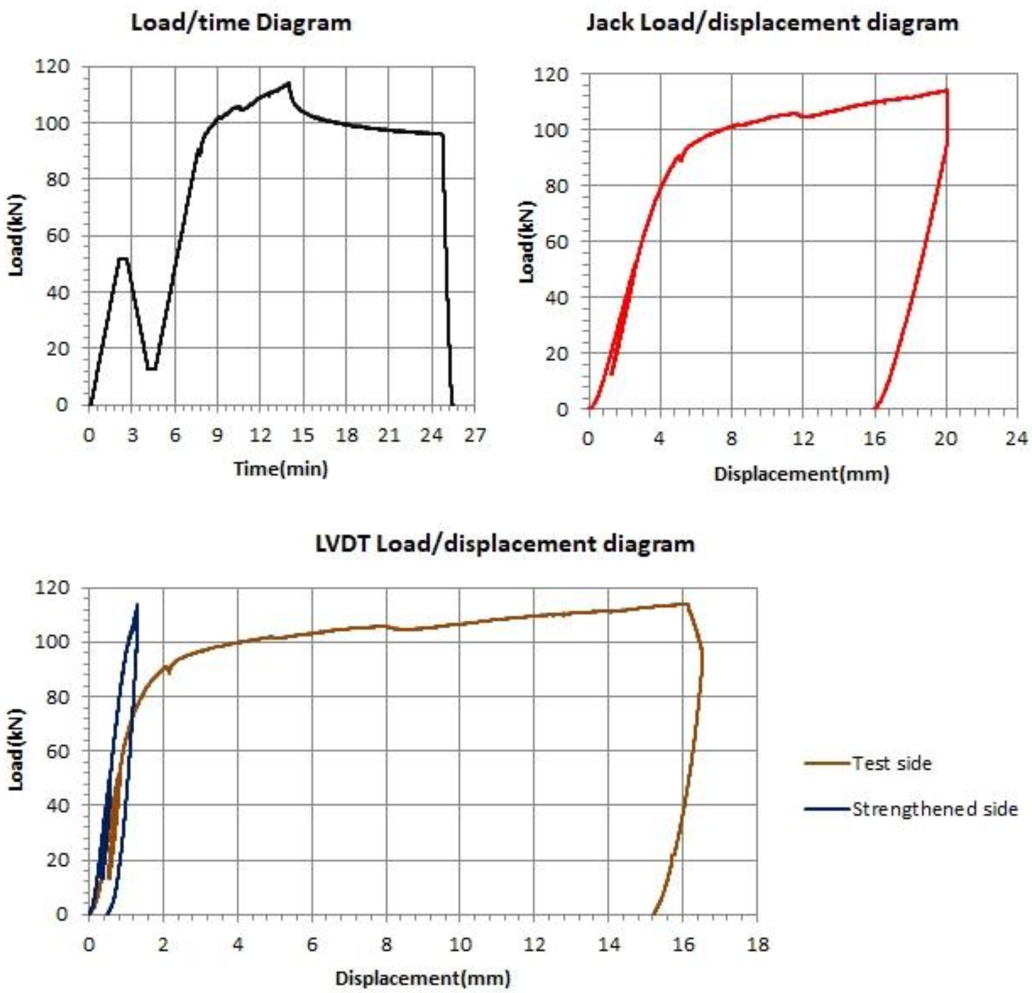


Figure 542 Graphical results of T40_A0_N2_2

13.16 T40_A0_N3

<u>Before Testing</u>(pictures test specimen T40_A0_N3_1 embedment/FM II failure)<u>:</u>

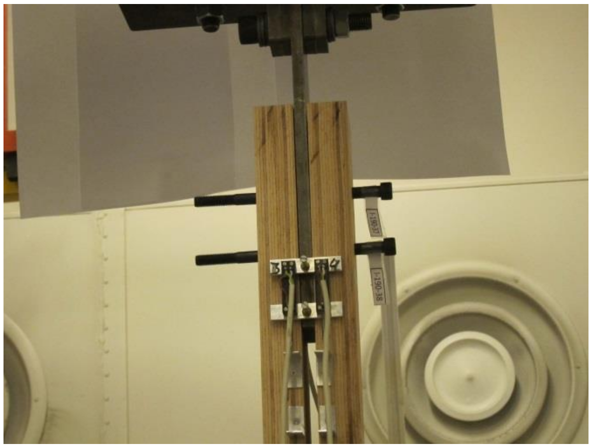


Figure 543 Front view

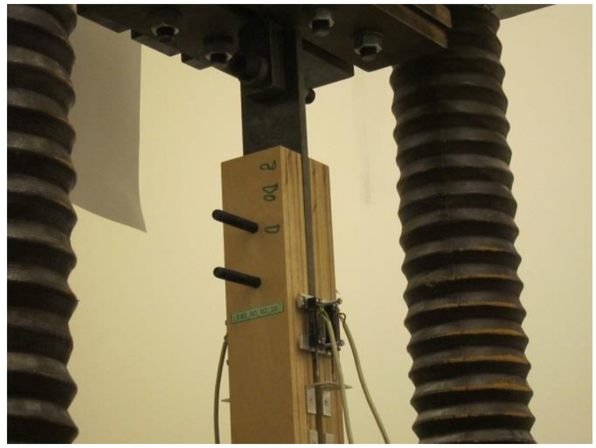


Figure 544 Perspective view nr. 1

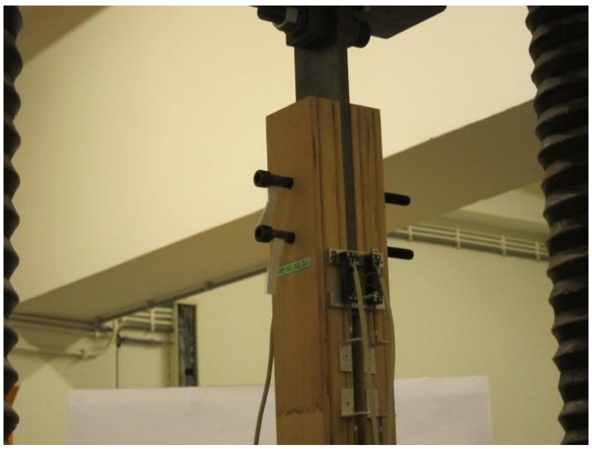


Figure 545 Perspective view nr 2

Figure 546 Overview materials

Figure 547 Overview materials

<u>After testing</u>

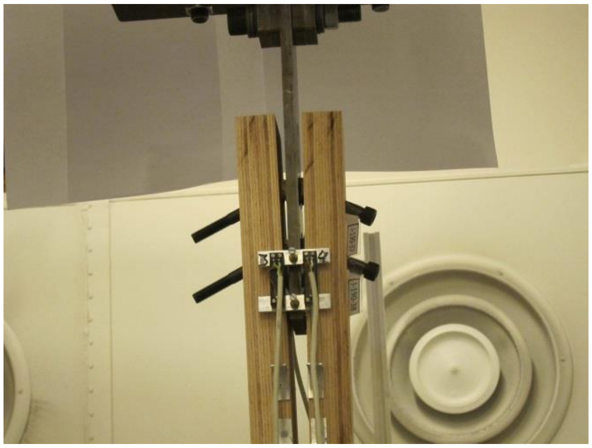


Figure 548 Front view

Figure 549 Perspective view nr. 1

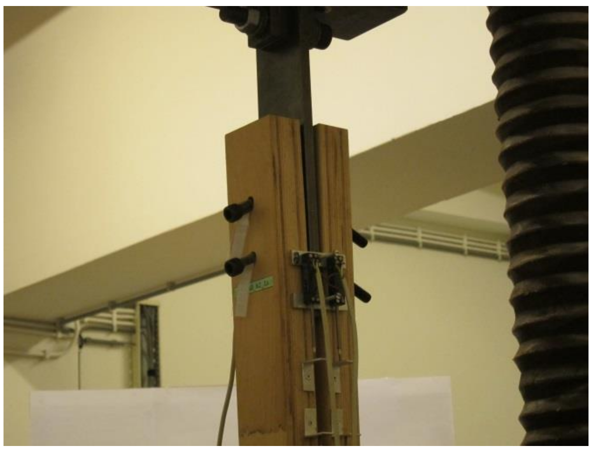


Figure 550 perspective view nr 2

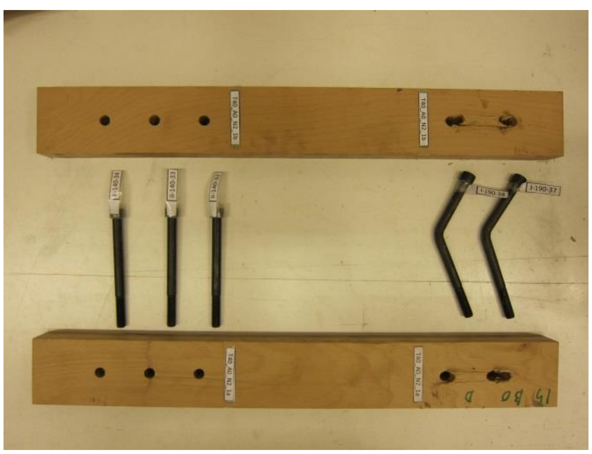


Figure 551 Overview materials

Figure 552 Overview materials

Figure 553 Closeup failure(Surface towards steel plate)

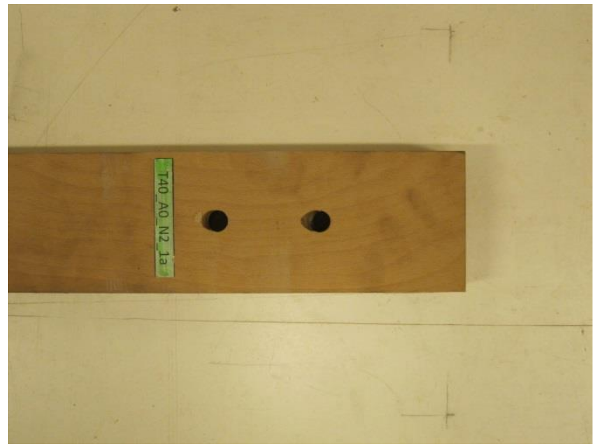


Figure 555 Closeup failure(Surface on the outside)

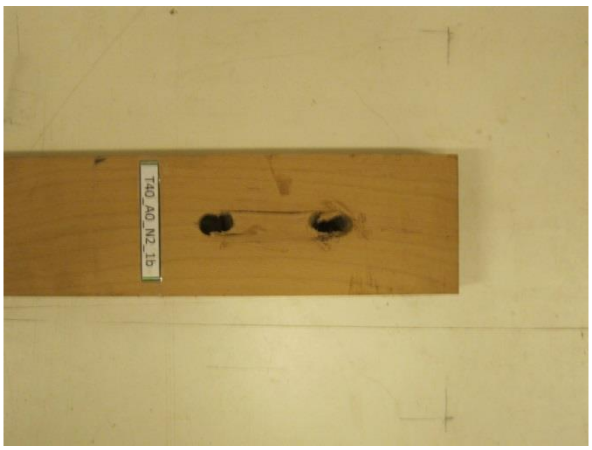


Figure 554 Closeup failure(Surface towards steel plate)

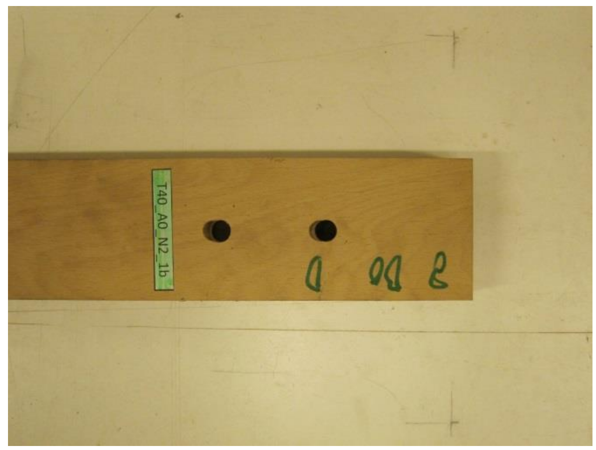


Figure 556 Closeup failure(Surface on the outside)

Figure 557 Dowels after testing strengthened side

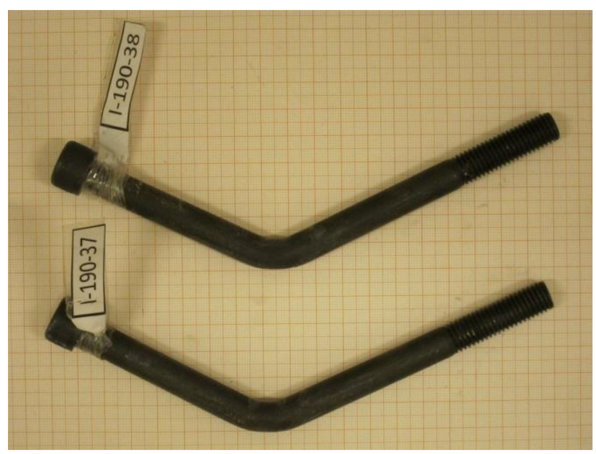


Figure 558 dowels after testing test side

13.16.1 T40_A0_N3_1

Material coding:

Labels Timber	T40_A0_N3_1a	T40_A0_N3_1b		
Labels Steel Test side	I-190-41	I-190-42	I-190-43	
Labels Steel Strengthened. side	II-140-38	II-140-39	II-140-40	II-140-41

Table 171 Material coding T40_A0_N3_1

Log:

Material: *clear specimen*

F_{est}: *180kN*
Displacement controlled speed(1): *0.04mm/s*
Displacement controlled speed(2): *mm/s*

During testing: *as planned*

Cause of failure: *embedment failure*

Additional remarks:

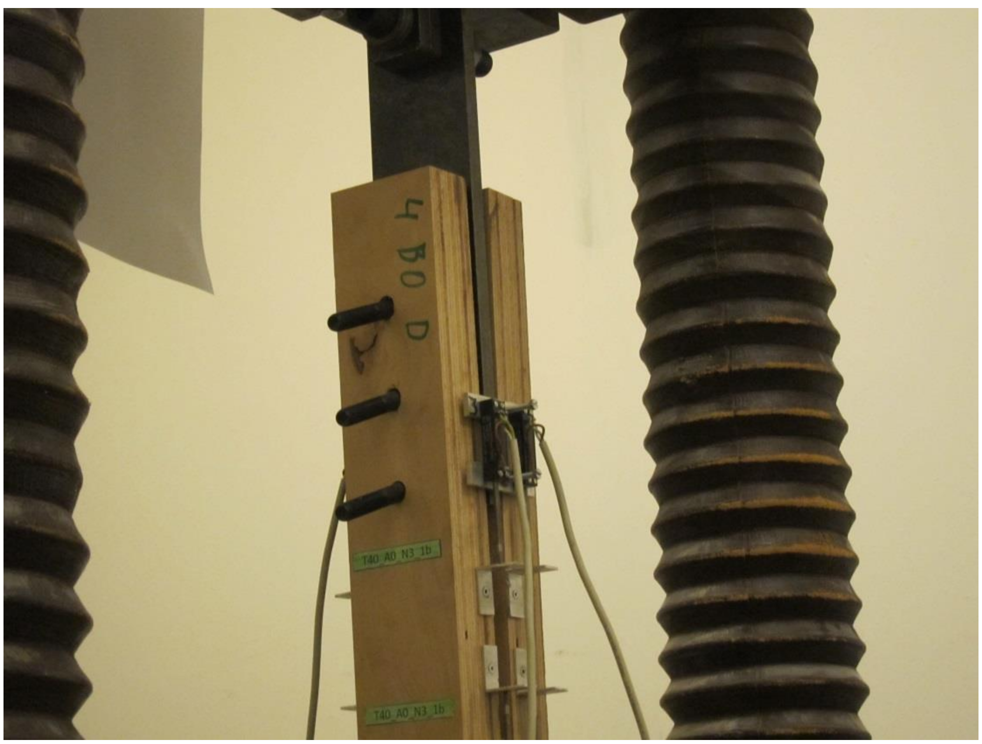


Figure 559 Perspective view nr1. After testing

Data:

T40_A0_N3_1	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	164,85	15,16	2,08	21,81	16,15
$F_{0,5}$	158,76	5,00	1,89	11,25	10,28
$F_{failure}$	-	-	-	-	-

Table 172 Results of specimen T40_A0_N3_1

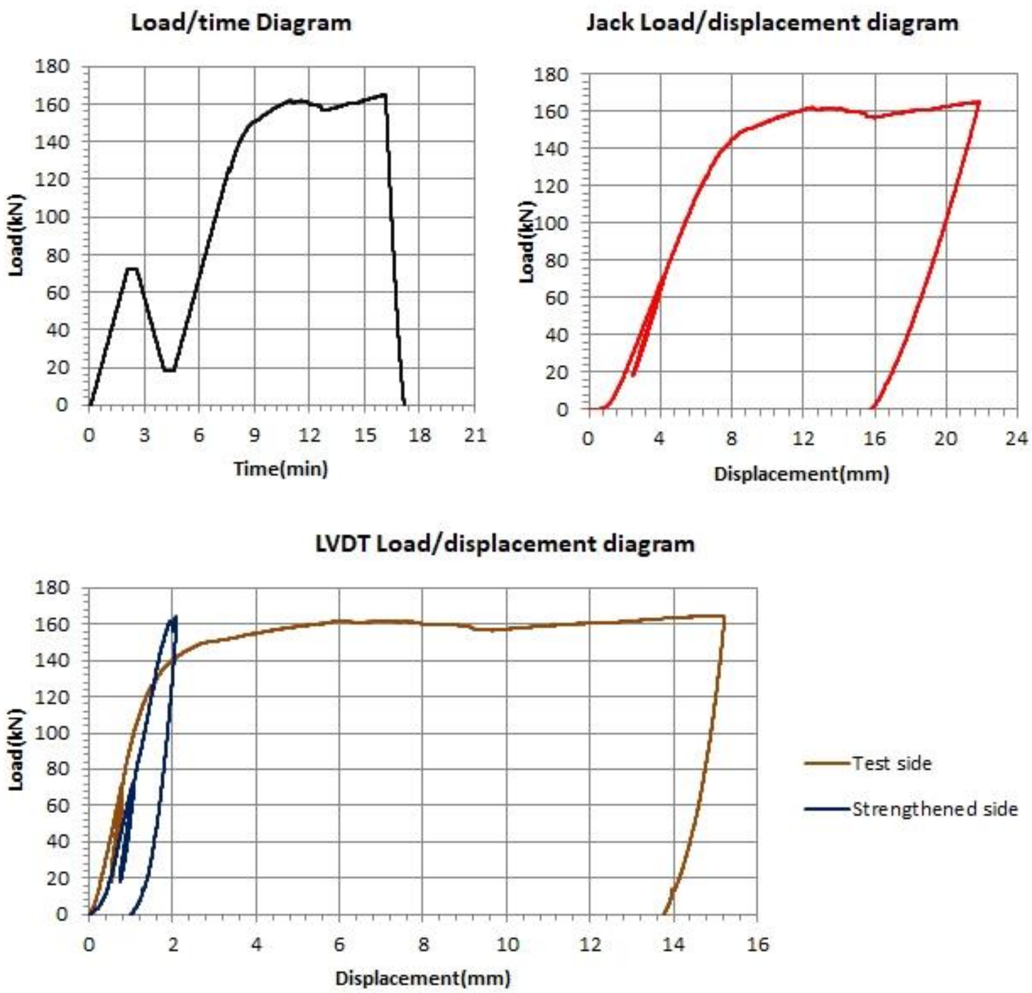


Figure 560 Graphical results of T40_A0_N3_1

13.16.2 T40_A0_N3_2

Material coding:

Labels Timber	T40_A0_N3_2a	T40_A0_N3_2b		
Labels Steel Test side	I-190-44	I-190-45	I-190-46	
Labels Steel Strengthened. side	II-140-42	II-140-43	II-140-44	II-140-45

Table 173 Material coding T40_A0_N3_2

Log:

Material: *clear specimen*

F_{est}: *130kN*
Displacement controlled speed(1): *0.04mm/s*
Displacement controlled speed(2): *mm/s*

During testing: *as planned*

Cause of failure: *embedment failure*

Additional remarks: *bending around 130kN after that timber tends to move sideways reducing capacity*

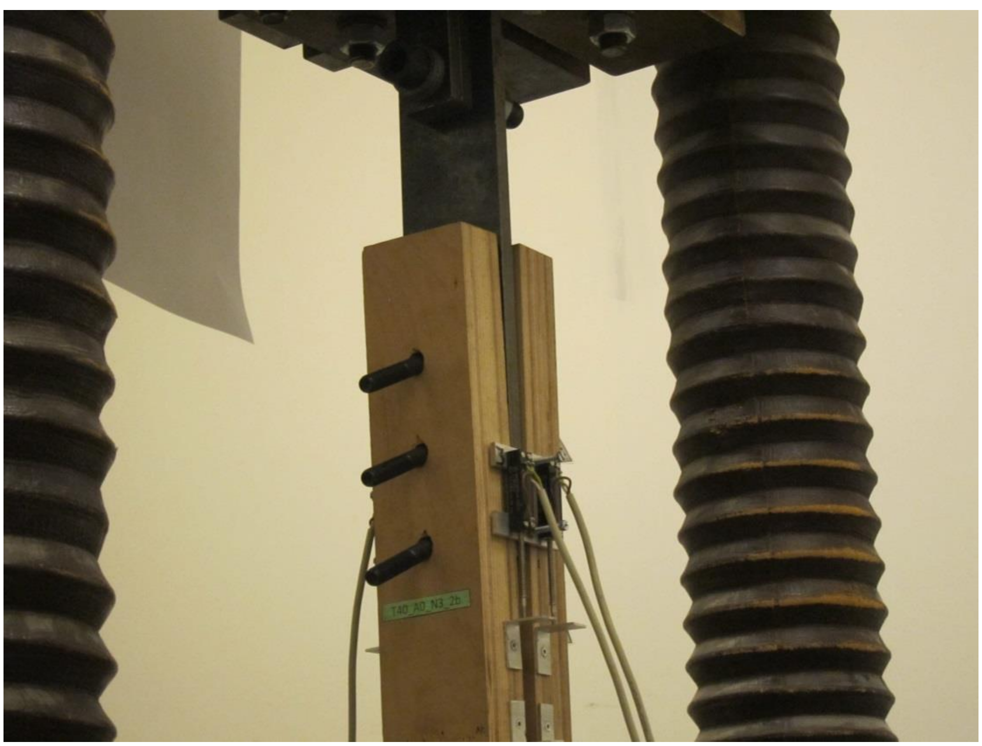
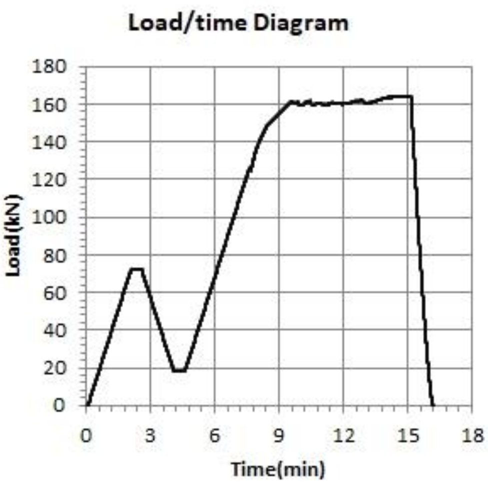


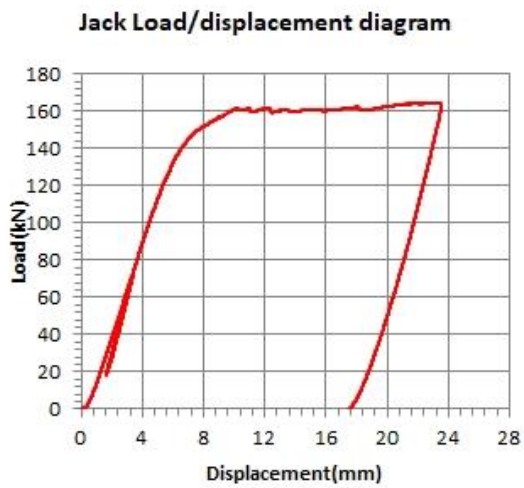
Figure 561 Perspective view nr1. After testing

Data:

T40_A0_N3_2	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	164,35	17,87	1,83	23,33	15,07
$F_{0,5}$	161,59	5,00	1,67	10,28	9,63
$F_{failure}$	-	-	-	-	-

Table 174 Results of specimen T40_A0_N3_2





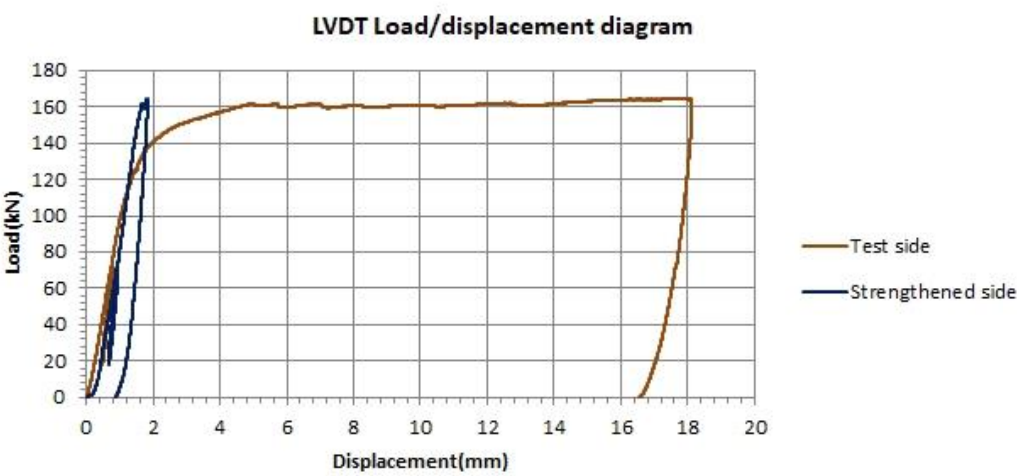


Figure 562 Graphical results of T40_A0_N3_2

13.17 T40_A90_N1

***Before Testing*(pictures test specimen T40_A90_N1_1 embedment/FM II failure):**

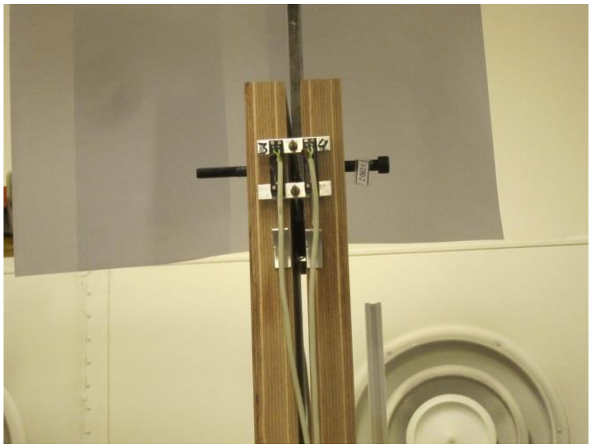


Figure 563 Front view

Figure 564 Perspective view nr. 1

Figure 565 Perspective view nr 2

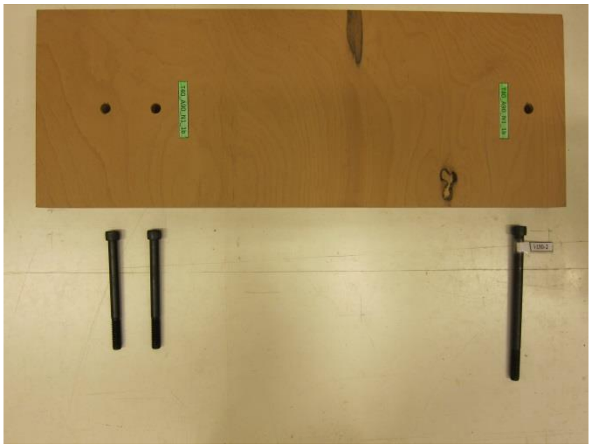


Figure 566 Overview materials

Figure 567 Overview materials

Figure 568 Overview materials

After testing

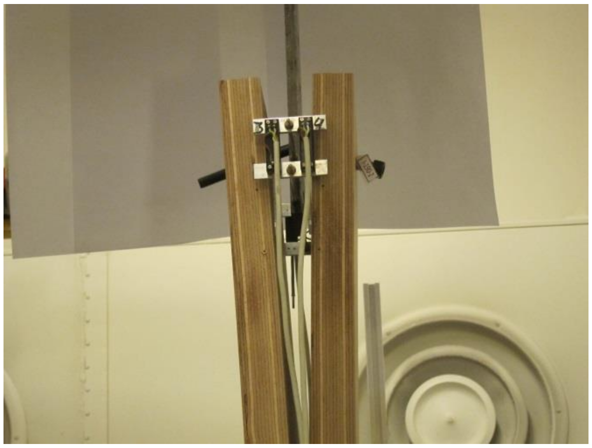


Figure 569 Front view


Figure 570 Perspective view nr. 1


Figure 571 perspective view nr 2


Figure 572 Overview materials


Figure 573 Overview materials


Figure 574 Overview materials

Figure 575 Closeup failure(Surface towards steel plate)

Figure 577 Closeup failure(Surface on the outside)

Figure 576 Closeup failure(Surface towards steel plate)

Figure 578 Closeup failure(Surface on the outside)

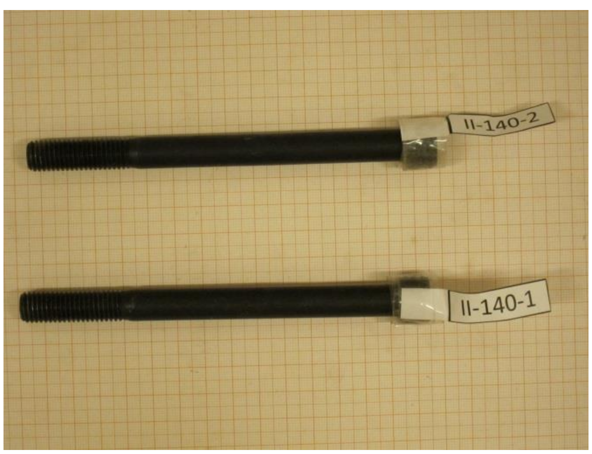


Figure 579 Dowels after testing strengthened side

Figure 580 dowels after testing test side

13.17.1 T40_A90_N1_1

Material coding:

Labels Timber	T40_A90_N1_1a	T40_A90_N1_1b
Labels Steel Test side	I-190-2	
Labels Steel Strengthened. side	II-140-1	II_140-2

Table 175 Material coding T40_A90_N1_1

Log:

Material: *clear specimen*

F_{est}: *60kN*
Displacement controlled speed(1): *0.04mm/s*
Displacement controlled speed(2): *mm/s*

During testing: *as planned*

Cause of failure: *embedment failure*

Additional remarks:

Figure 581 Perspective view nr1. After testing

Data:

T40_A90_N1_1	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	53,37	12,02	1,60	15,29	11,99
$F_{0,5}$	48,82	5,00	1,46	7,86	8,90
$F_{failure}$	-	-	-	-	-

Table 176 Results of specimen T40_A90_N1_1

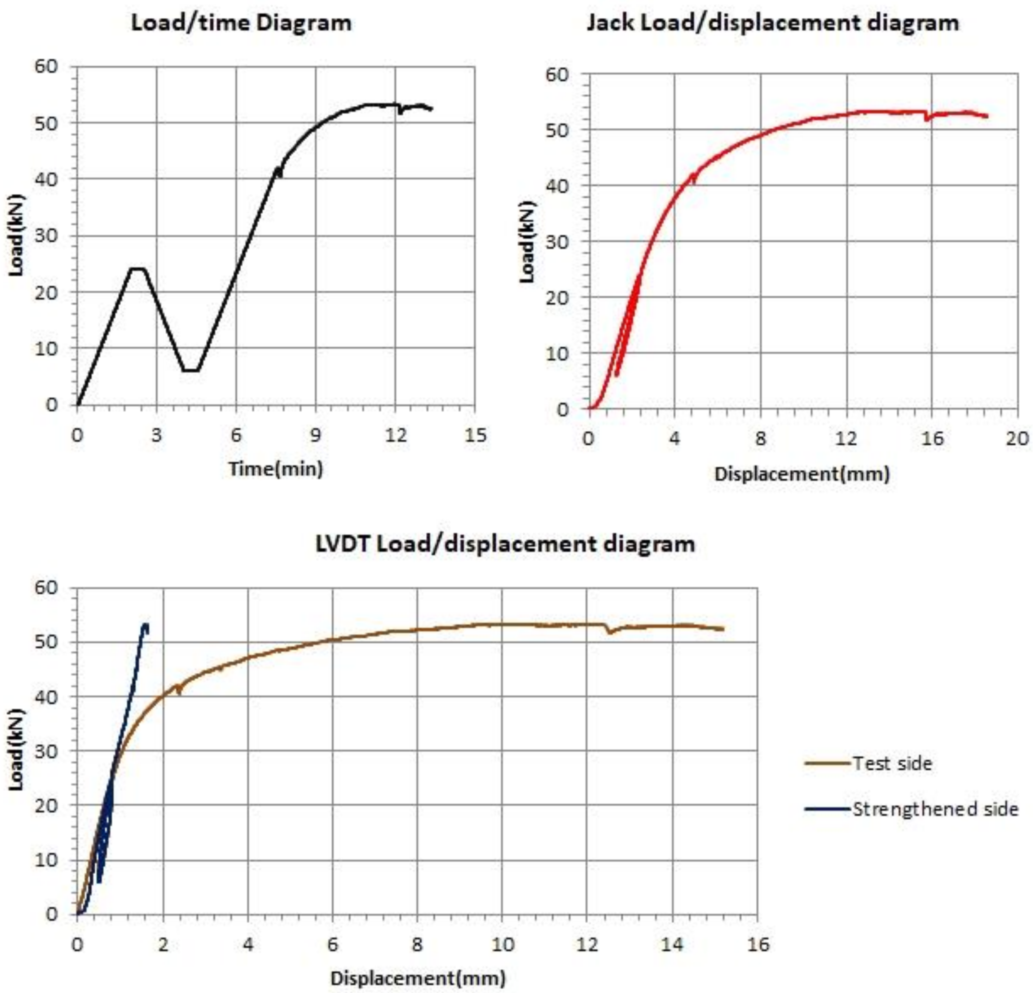


Figure 582 Graphical results of T40_A90_N1_1

13.17.2 T40_A90_N1_2

Material coding:

Labels Timber	T40_A90_N1_2a	T40_A90_N1_2b
Labels Steel Test side	I-190-3	
Labels Steel Strengthened. side	II-140-3	II_140-4

Table 177 Material coding T40_A90_N1_2

Log:

Material: *clear specimen, except for some discolouration*
F_{est}: *55kN*
Displacement controlled speed(1): *0.03mm/s*
Displacement controlled speed(2): *mm/s*

During testing: *as planned*

Cause of failure: *embedment failure*

Additional remarks:

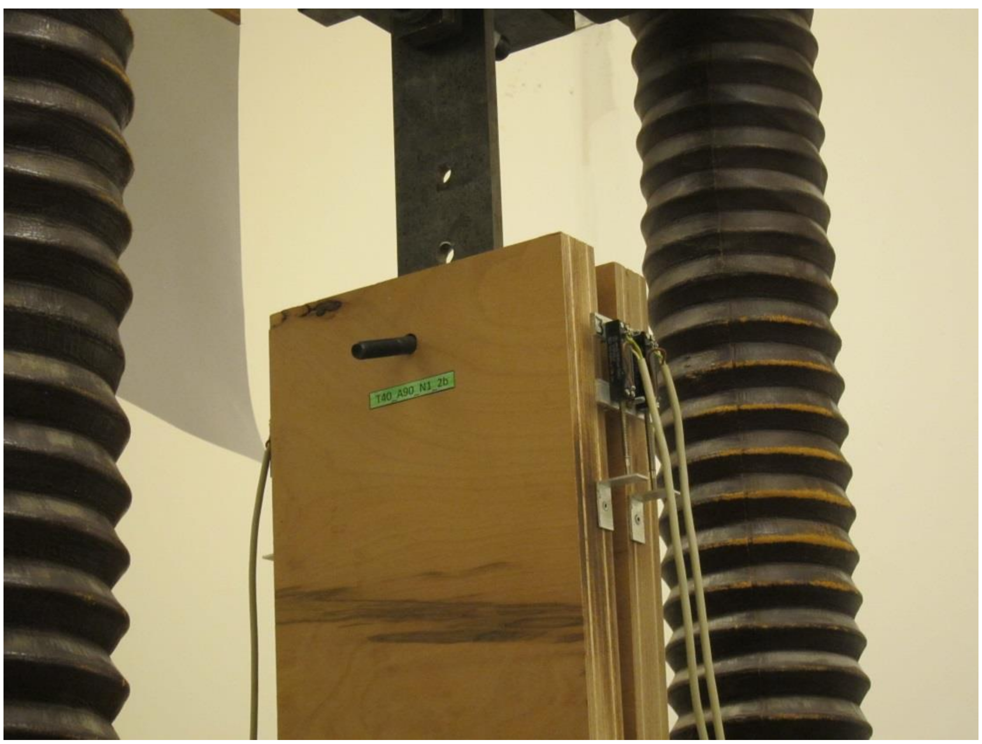
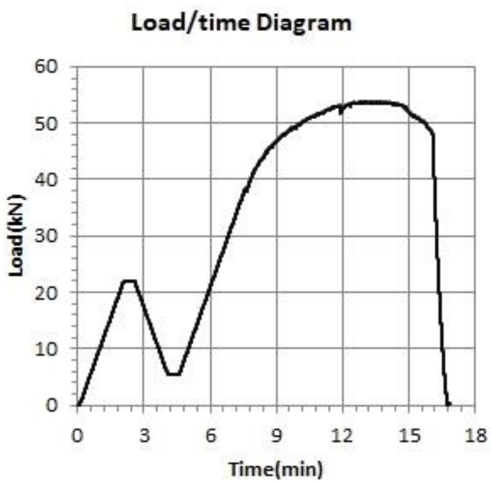


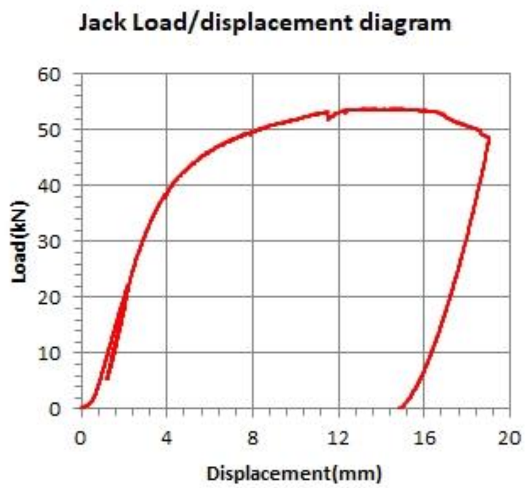
Figure 583 Perspective view nr1. After testing

Data:

T40_A90_N1_2	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	53,77	11,70	1,27	14,75	13,70
$F_{0,5}$	49,14	5,00	1,06	7,59	9,72
$F_{failure}$	-	-	-	-	-

Table 178 Results of specimen T40_A90_N1_2





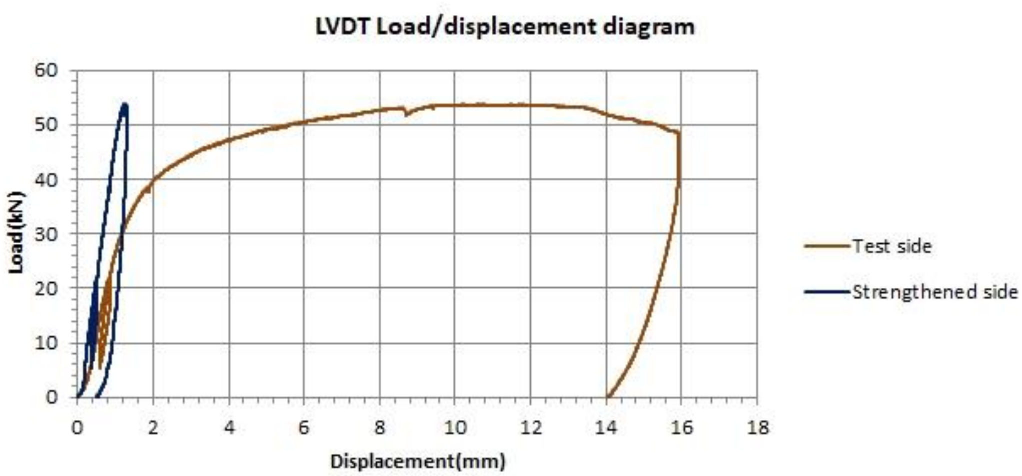


Figure 584 Graphical results of T40_A90_N1_2

13.18 T40_A90_N2

Before Testing ***(pictures test specimen T40_A90_N2_1 embedment/FM II failure):***

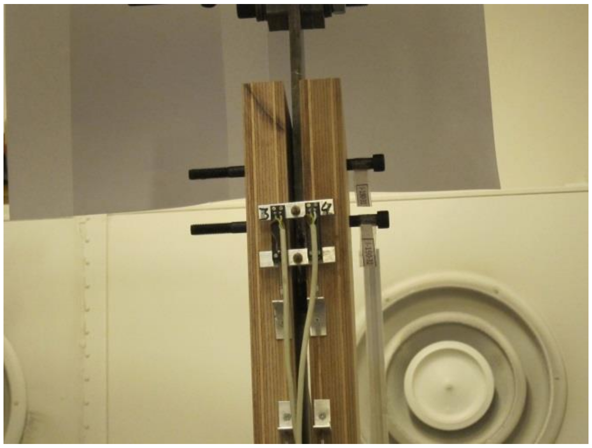


Figure 585 Front view

Figure 586 Perspective view nr. 1

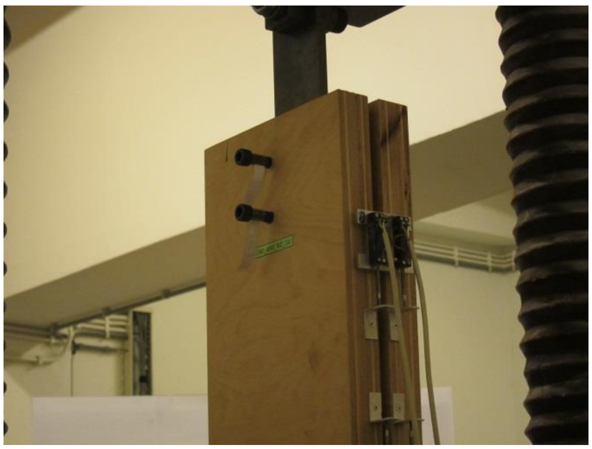


Figure 587 Perspective view nr 2

Figure 588 Overview materials

Figure 589 Overview materials

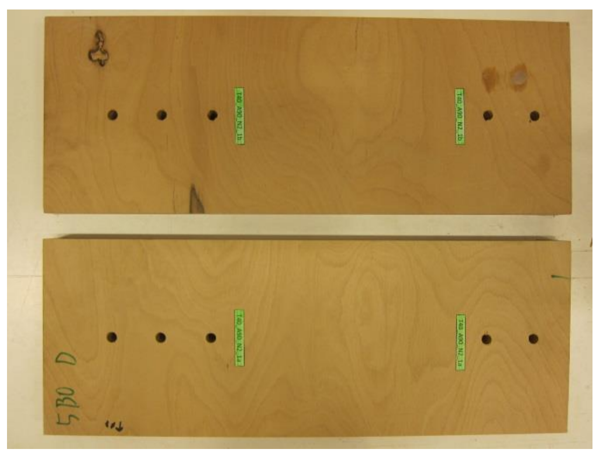


Figure 590 Overview materials

After testing

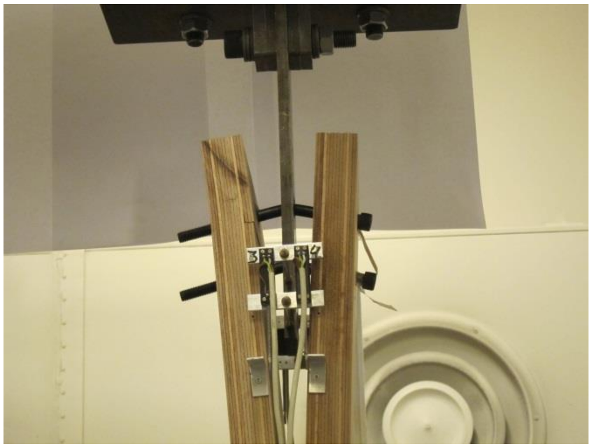


Figure 591 Front view

Figure 592 Perspective view nr. 1

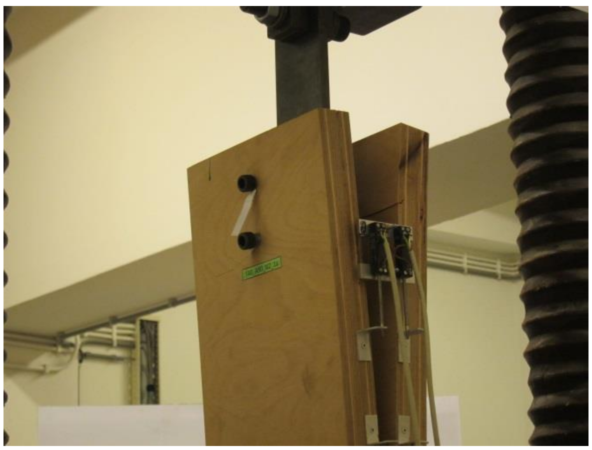


Figure 593 perspective view nr 2

Figure 594 Overview materials

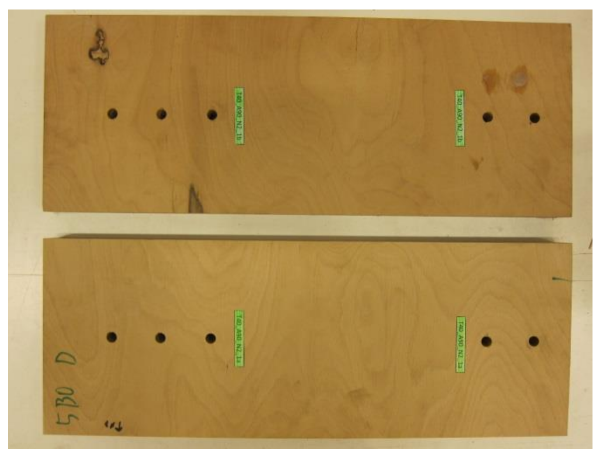


Figure 595 Overview materials

Figure 596 Overview materials

Figure 597 Closeup failure(Surface towards steel plate)

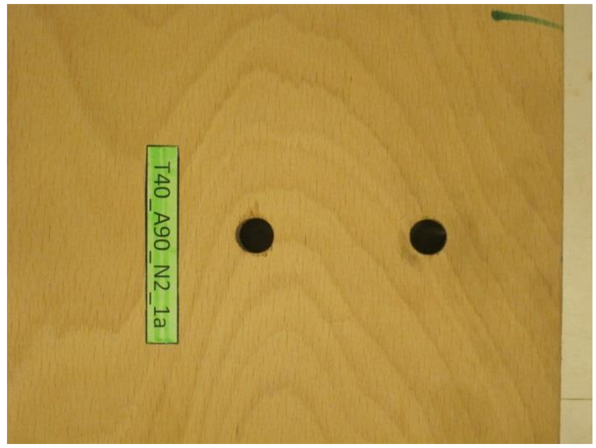


Figure 599 Closeup failure(Surface on the outside)

Figure 598 Closeup failure(Surface towards steel plate)

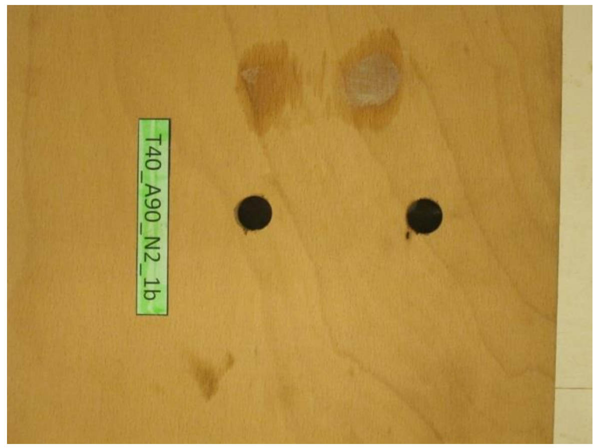


Figure 600 Closeup failure(Surface on the outside)

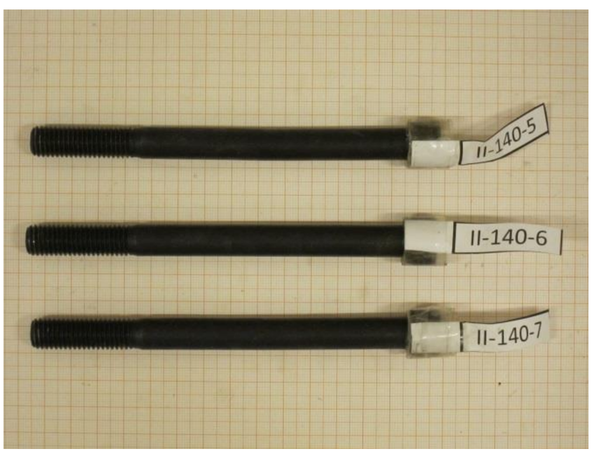


Figure 601 Dowels after testing strengthened side

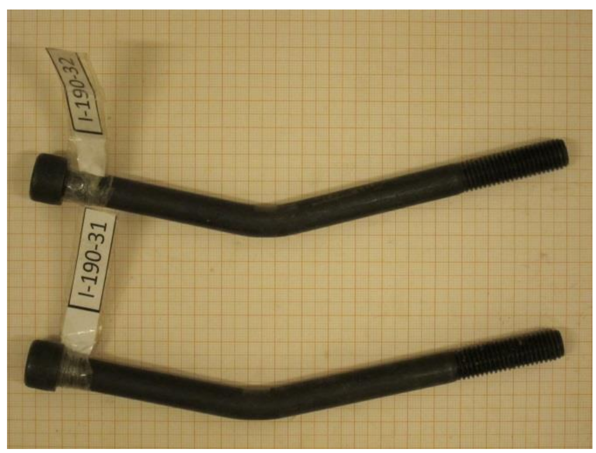


Figure 602 dowels after testing test side

13.18.1 T40_A90_N2_1

Material coding:

Labels Timber	T40_A90_N2_1a	T40_A90_N2_1b	
Labels Steel Test side	I-190-31	I-190-32	
Labels Steel Strengthened. side	II-140-5	II_140-6	II_140-7

Table 179 Material coding T40_A90_N2_1

Log:

Material: *clear specimen*

F_{est}: *110kN*
Displacement controlled speed(1): *0.04mm/s*
Displacement controlled speed(2): *mm/s*

During testing: *as planned*

Cause of failure: *tensile failure*

Additional remarks:

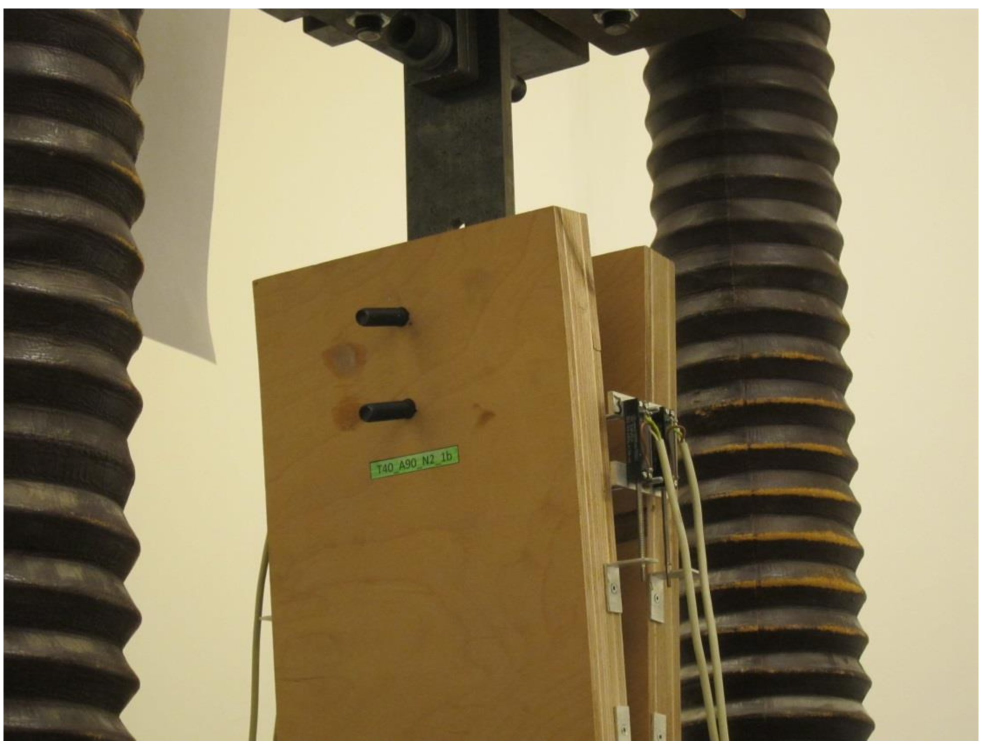
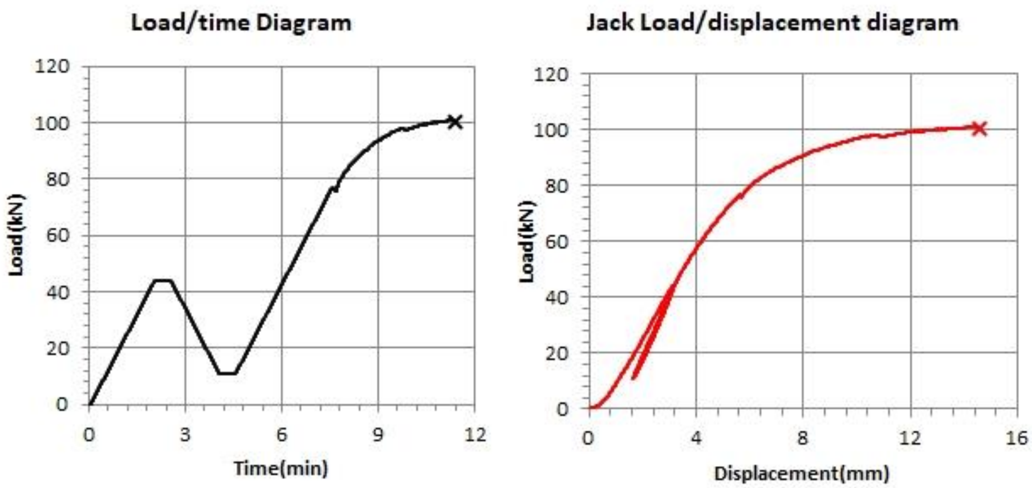


Figure 603 Perspective view nr1. After testing

Data:

T40_A90_N2_1	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	101,07	9,60	2,18	14,39	11,32
$F_{0,5}$	95,48	5,00	1,99	9,45	9,26
$F_{failure}$	100,31	9,85	2,20	14,63	11,42

Table 180 Results of specimen T40_A90_N2_1



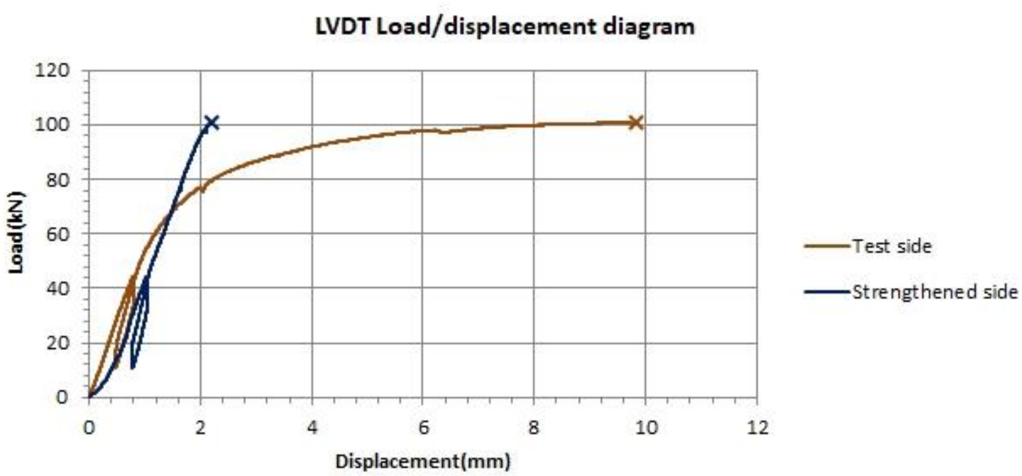


Figure 604 Graphical results of T40_A90_N2_1

13.18.2 T40_A90_N2_2

Material coding:

Labels Timber	T40_A90_N2_2a	T40_A90_N2_2b	
Labels Steel Test side	I-190-33	I-190-34	
Labels Steel Strengthened. side	II-140-8	II_140-9	II_140-10

Table 181 Material coding T40_A90_N2_2

Log:

Material: *clear specimen*

F_{est}: *110kN*
Displacement controlled speed(1): *0.04mm/s*
Displacement controlled speed(2): *mm/s*

During testing: *as planned*

Cause of failure: *tensile failure*

Additional remarks: a lot of brute force was needed to dismantle the test pieces

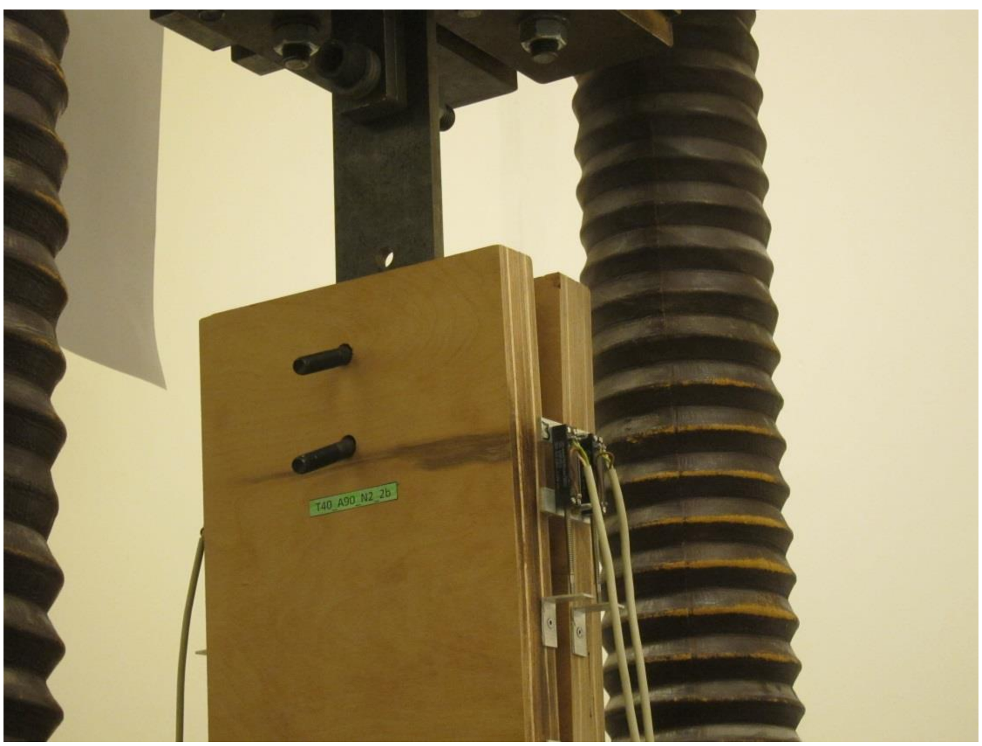


Figure 605 Perspective view nr1. After testing

Data:

T40_A90_N2_2	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	114,14	13,46	2,81	19,11	13,24
$F_{0,5}$	97,18	5,00	2,32	9,69	9,32
$F_{failure}$	-	-	-	-	-

Table 182 Results of specimen T40_A90_N2_2

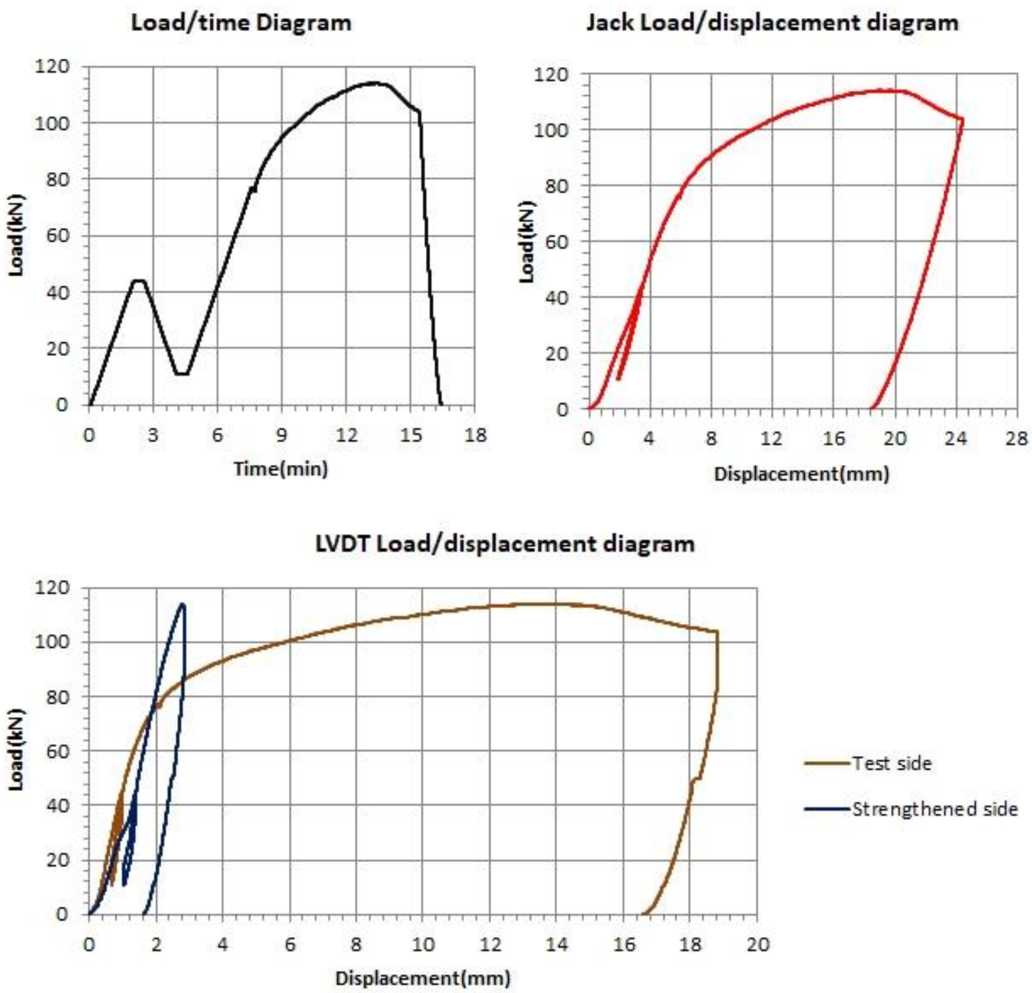


Figure 606 Graphical results of T40_A90_N2_2

13.19 T40_A90_N3

***Before Testing**(pictures test specimen T40_A90_N3_1 embedment/FM II failure):*

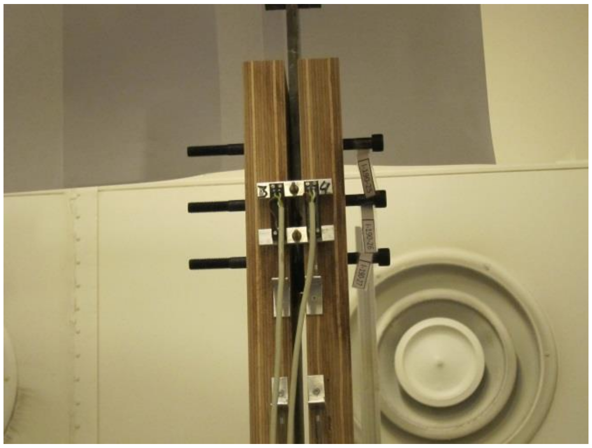


Figure 607 Front view

Figure 608 Perspective view nr. 1

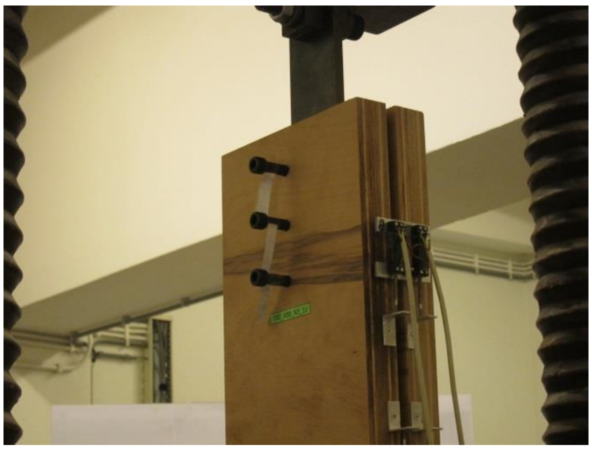


Figure 609 Perspective view nr 2

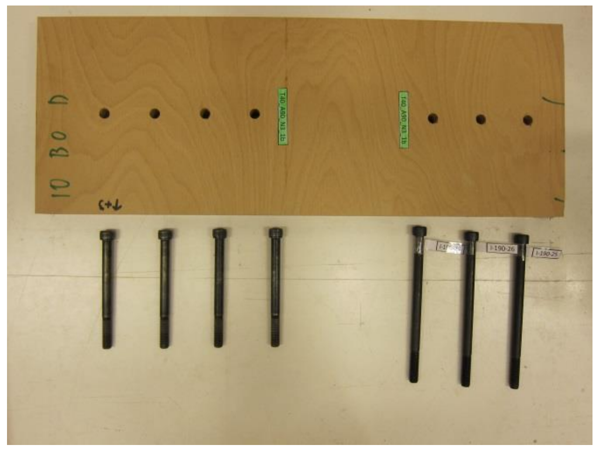


Figure 610 Overview materials

Figure 611 Overview materials

Figure 612 Overview materials

After testing

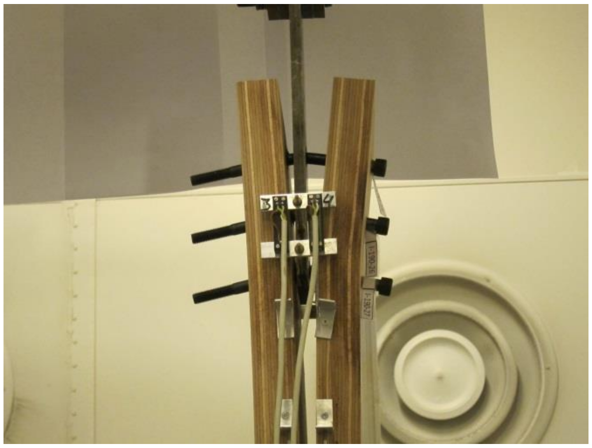


Figure 613 Front view

Figure 614 Perspective view nr. 1

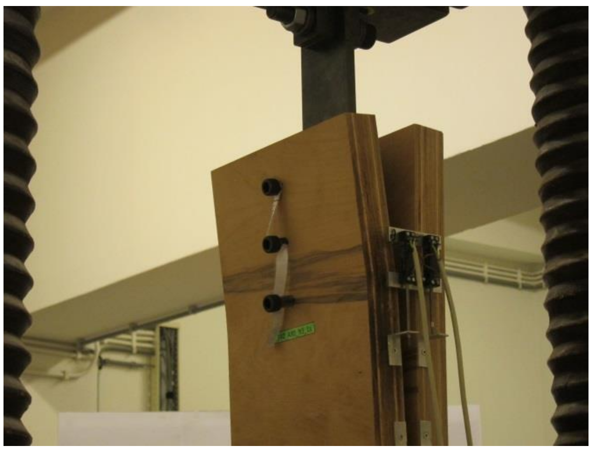


Figure 615 perspective view nr 2

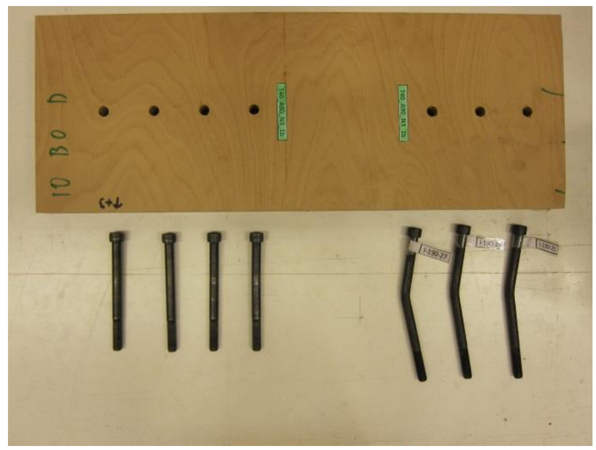


Figure 616 Overview materials

Figure 617 Overview materials

Figure 618 Overview materials

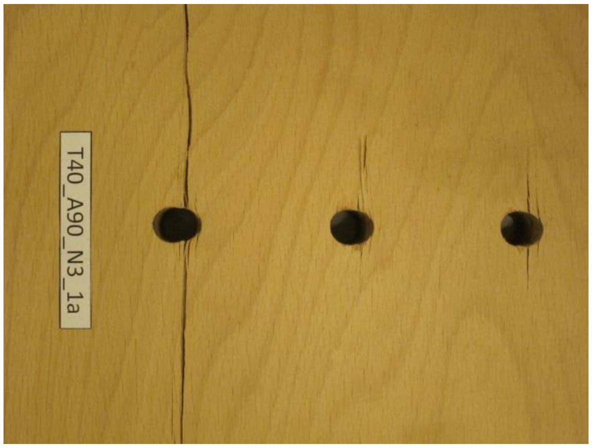


Figure 619 Closeup failure(Surface towards steel plate)

Figure 621 Closeup failure(Surface on the outside)

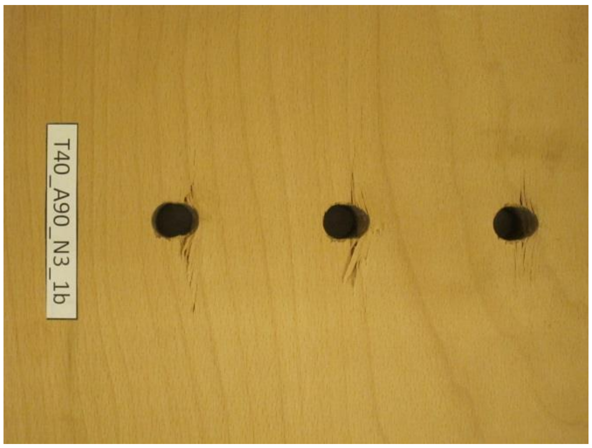


Figure 620 Closeup failure(Surface towards steel plate)

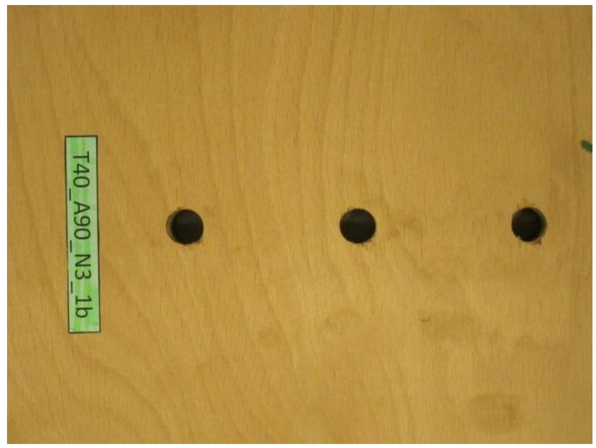


Figure 622 Closeup failure(Surface on the outside)

Figure 623 Dowels after testing strengthened side

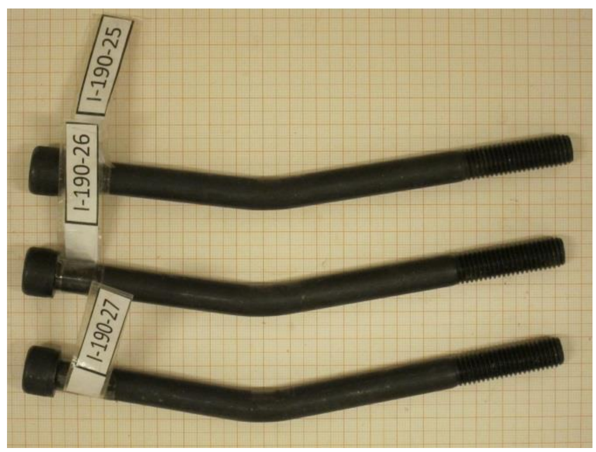


Figure 624 dowels after testing test side

13.19.1 T40_A90_N3_1

Material coding:

Labels Timber	T40_A90_N3_1a	T40_A90_N3_1b		
Labels Steel Test side	I-190-25	I-190-26	I-190-27	
Labels Steel Strengthened. side	reused	reused	reused	reused

Table 183 Material coding T40_A90_N3_1

Log:

Material: *clear specimen*

F_{est}: *100kN*

Displacement controlled speed(1): *0.03mm/s*

Displacement controlled speed(2): *mm/s*

During testing: *as planned*

Cause of failure: *tensile failure*

Additional remarks:

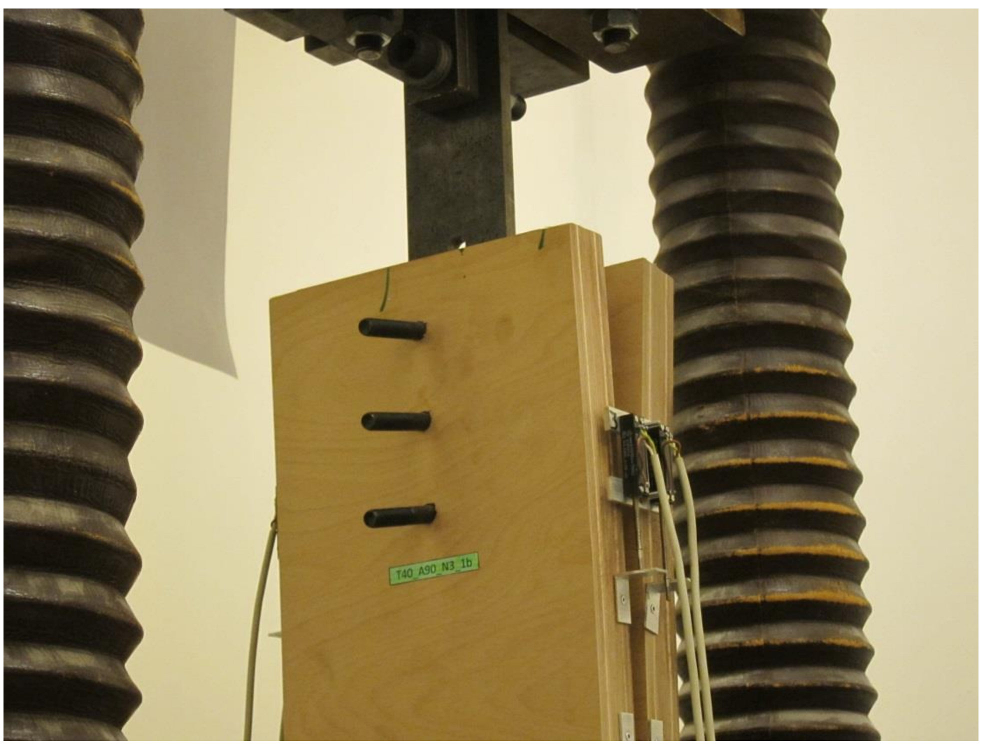


Figure 625 Perspective view nr1. After testing

Data:

T40_A90_N3_1	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	153,45	6,72	2,89	13,36	15,70
$F_{0,5}$	146,77	5,00	2,75	11,23	13,93
$F_{failure}$	153,28	6,75	2,91	13,39	15,73

Table 184 Results of specimen T40_A90_N3_1

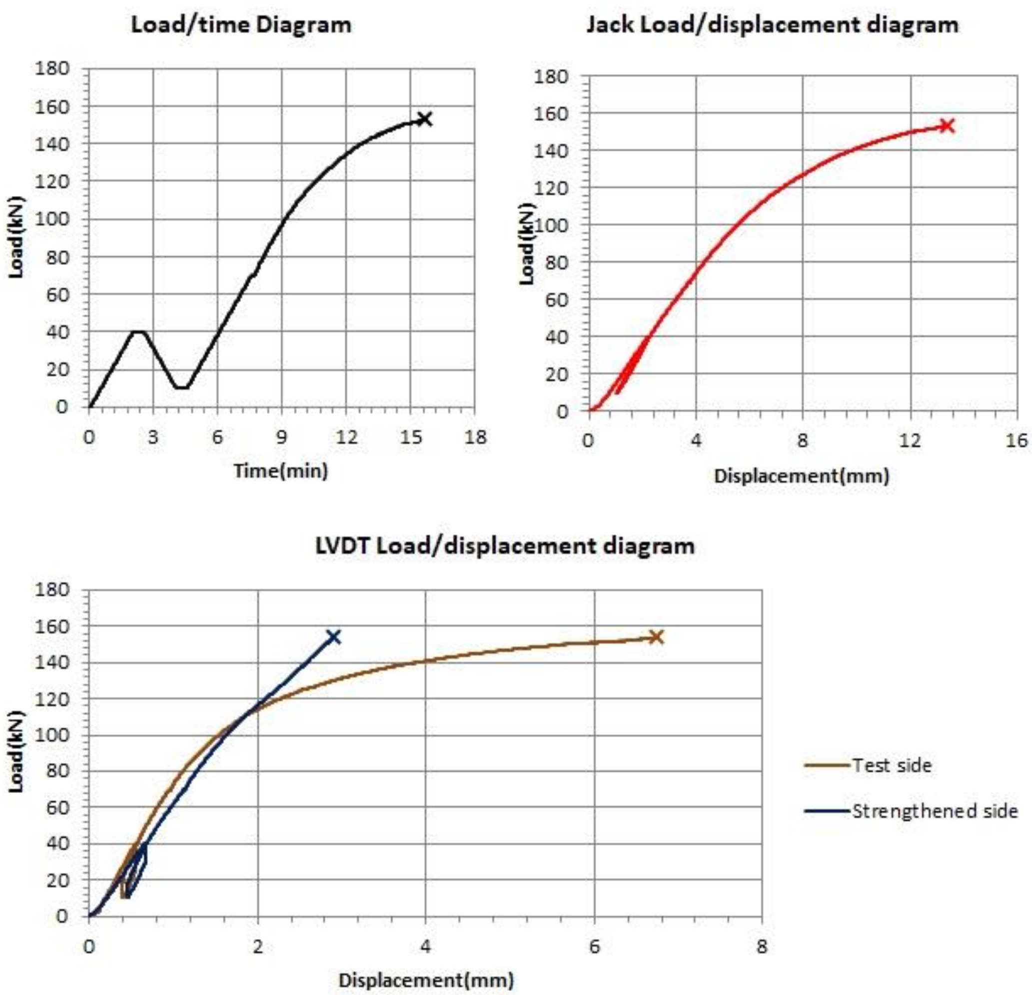


Figure 626 Graphical results of T40_A90_N3_1

13.19.2 T40_A90_N3_2

Material coding:

Labels Timber	T40_A90_N3_2a	T40_A90_N3_2b		
Labels Steel Test side	I-190-28	I-190-29	I-190-30	
Labels Steel Strengthened. side	I-140-37	I-140-38	I-140-39	I-140-40

Table 185 Material coding T40_A90_N3_2

Log:

Material: *clear specimen*

F_{est}: *140kN*
Displacement controlled speed(1): *0.03mm/s*
Displacement controlled speed(2): *mm/s*

During testing: *as planned*

Cause of failure: *tensile failure*

Additional remarks:

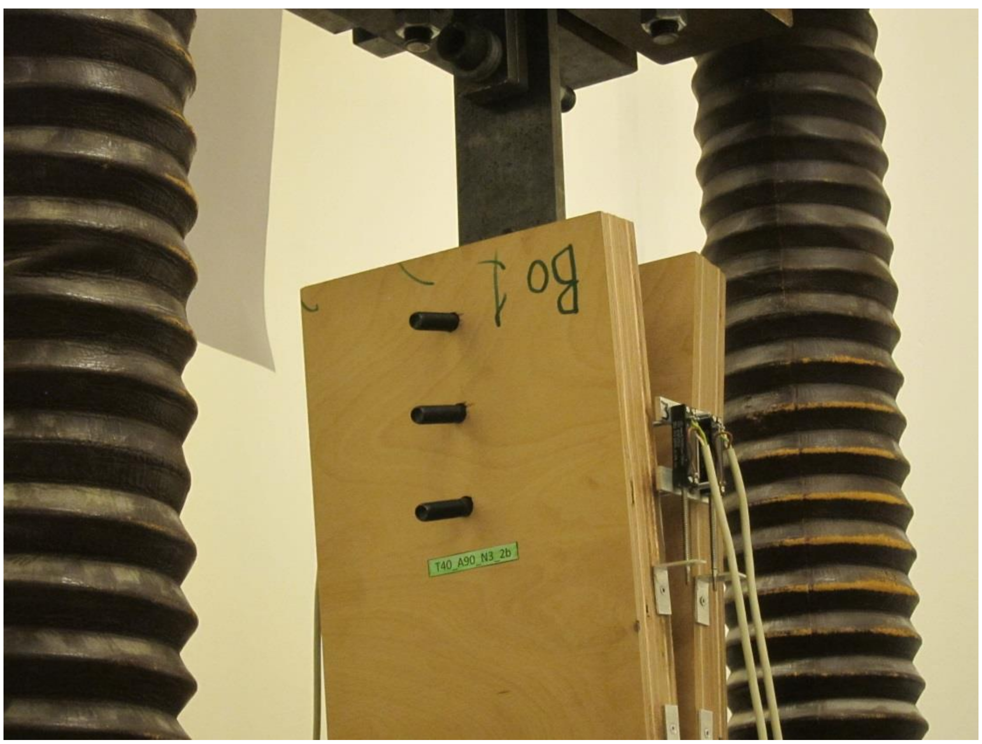
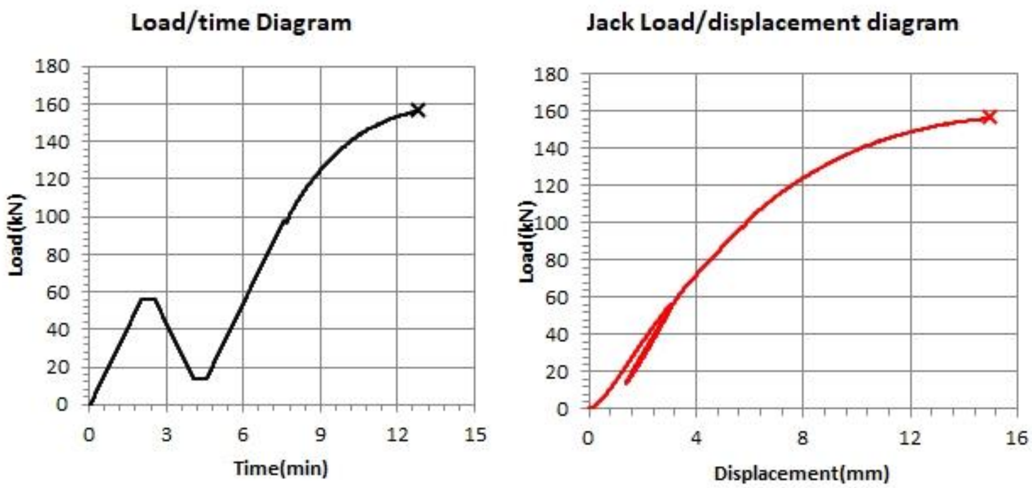


Figure 627 Perspective view nr1. After testing

Data:

T40_A90_N3_2	Load(kN)	v_{test}(mm)	$v_{strength}$(mm)	v_{jack}(mm)	t(min)
F_{max}	132,37	2,98	2,82	9,00	9,51
$F_{0,5}$	147,56	4,99	3,17	11,69	11,01
$F_{failure}$	156,19	7,80	3,42	14,97	12,83

Table 186 Results of specimen T40_A90_N3_2



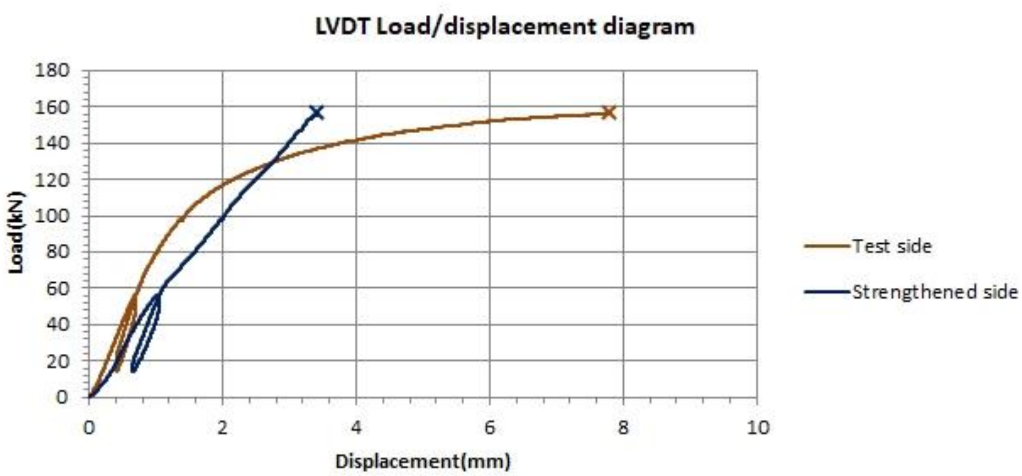


Figure 628 Graphical results of T40_A90_N3_2