Dowel type connections in laminated bamboo with multiple slotted-in steel plates

Annex C – Design of test pieces

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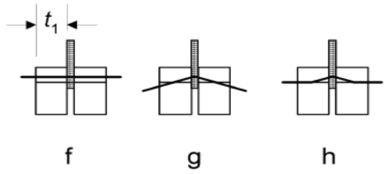
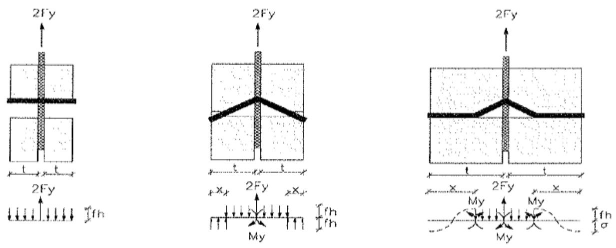
The maximum resistance of the connection is calculated according to NEN-EN 1995-1-1+C1+A1=2001. The claculation rules for the resistance per shear plane per dowel are given in chapter 8.2. For a connection where a steel plate is slotted-in three different failure modes are considered (assuming the steel plate does not fail).

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



For Smooth dowels the withdrawal resistance $F_{ax,Rk}$ in these formulas is taken to be 0. The Eurocode accounts for an extra frictional resistance in these formulas (Pedersen, 1999). Pedersen does not take this into account and gives the following formulas to determine the resistance:



(a) Mode I (b) Mode II (c) Mode III

$$F_y = min \begin{cases} t\, d\, f_h & \text{for } t < \sqrt{\frac{2M_y}{d f_h}} & \text{Mode I} \\ \left(\sqrt{2 + 4 \frac{M_y}{t^2 d f_h}} - 1 \right) t\, d\, f_h & \text{for } \sqrt{\frac{2M_y}{d f_h}} \le t < \sqrt{\frac{16 M_y}{d f_h}} & \text{Mode II} \\ \sqrt{4 M_y\, d\, f_h} & \text{for } t \ge \sqrt{\frac{16 M_y}{d f_h}} & \text{Mode III} \end{cases}$$

These formulas seem to determine a more exact resistance and will be used for determining the theoretical failure load in this research. The moment restistance for a dowel is (according to chapter 8.5 of EC5 (Bolts)):

$$M_{y,Rk} = 0{,}3 f_{u,k} d^{2,6} \qquad (8.30)$$

waarin:

$M_{y,Rk}$ is de karakteristieke waarde van het vloeimoment, in Nmm;

$f_{u,k}$ is de karakteristieke treksterkte, in N/mm²;

d is de boutdiameter, in mm.

The moment resistance from Eurocode 5 accounts for a reduction in capacity for large diameter dowels. The theoretical moment resistance (without any redutctions) would be:

$M_y = 1/6 * f_y * d^3$

$M_y = 1/6 * 0.8 * f_u * d^3$ (Jorissen, 2005)

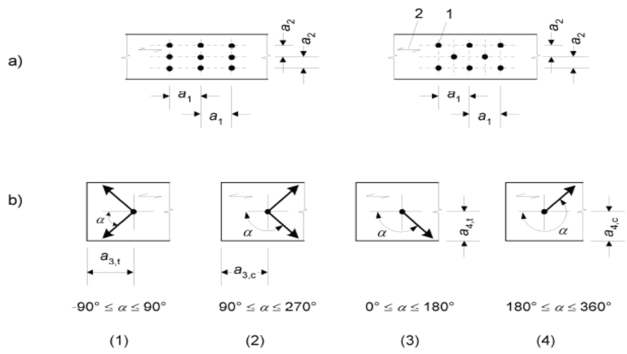
The embedment strength for a dowel is (according to chapter 8.5 (Bolts)):

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

Considering the density of laminated bamboo, the embedment strenght for hardwood species as given by Ehlbeck and Werner in 1992 (Sandhaas, 2012) (Islamaj, 2009) may be more applicable. This formula considers the avarage density of the wood instead of the characteristic density.

$f_{h,0} = 0.102(1\text{-}0.01d)\rho_{average}$

The used fastener spacings will be taken from Eurocode 5. These spacings are:



Verklaring

(1) belaste eindafstand
(2) onbelaste eindafstand
(3) belaste randafstand
(4) onbelaste randafstand
1 verbindingsmiddel
2 vezelrichting

Figuur 8.7 — Tussen-, eind- en randafstanden
a) tussenafstand evenwijdig aan de vezelrichting in een rij en loodrecht op de vezelrichting tussen rijen, b) rand- en eindafstanden

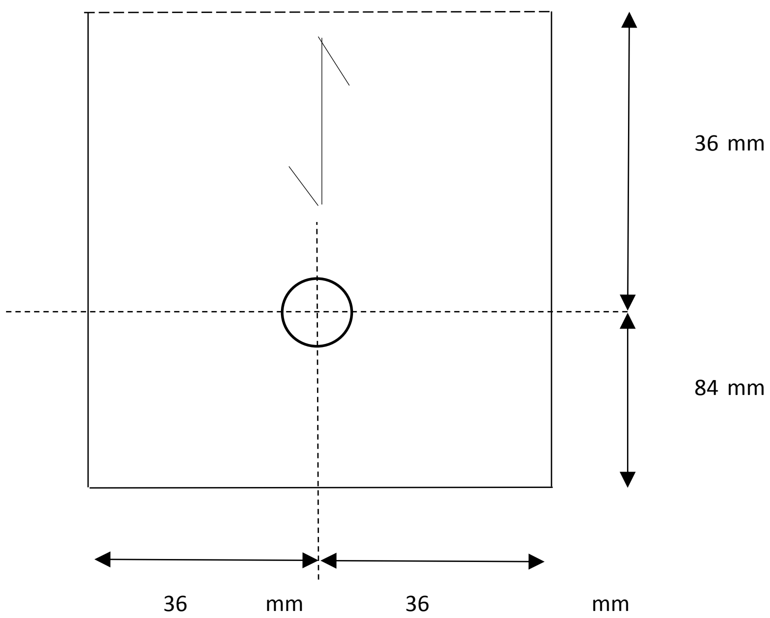
Tabel 8.5 — Minimale tussen-, eind- en randafstanden voor stiften

Tussen-, eind- randafstanden (zie figuur 8.7)	Hoek	Minimale tussen-, eind- en randafstanden
a_1 (evenwijdig aan de vezelrichting)	$0^\circ \leq \alpha \leq 360^\circ$	$(3 + 2\lvert\cos\alpha\rvert)\, d$
a_2 (loodrecht op de vezelrichting)	$0^\circ \leq \alpha \leq 360^\circ$	$3d$
$a_{3,t}$ (belast eind)	$-90^\circ \leq \alpha \leq 90^\circ$	max (7d; 80 mm)
$a_{3,c}$ (onbelast eind)	$90^\circ \leq \alpha < 150^\circ$ $150^\circ \leq \alpha < 210^\circ$ $210^\circ \leq \alpha \leq 270^\circ$	$\max(a_{3,t}\,\lvert\sin\alpha\rvert)\, d; 3d)$ $3d$ $\max(a_{3,t}\,\lvert\sin\alpha\rvert)\, d; 3d)$
$a_{4,t}$ (belaste rand)	$0^\circ \leq \alpha \leq 180^\circ$	$\max([2 + 2\sin\alpha)\, d; 3d)$
$a_{4,c}$ (onbelaste rand)	$180^\circ \leq \alpha \leq 360^\circ$	$3d$

For a connection using one bolt this leads to:

Dowel diameter $\phi_{dowel,1}$ 12 mm

Loading angle to fibre: α 0 rad



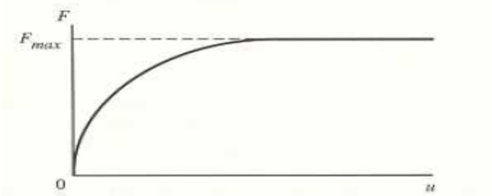
Dowel 1:

Diameter	$\o_{dowel,1}$	12	mm	
Tensile strength	f_u	510	N/mm²	(according to specifications)
		612	N/mm²	(accounting for 20% higher strength than specified)
Yield stress	f_y	355	N/mm²	(according to specifications)
Shear resistance	$F_{v,Rd}$	27.7	kN	(NEN-en 1993-1-8 table 3.10)
Embedment capacity	$F_{b,Rd}$	6.4	kN/mm	(NEN-en 1993-1-8 table 3.10)
Moment capacity	M_y	97850.4147	Nmm	(Volgens EC5)
		102240	Nmm	(According to Meyer (Jorissen, 2005))
		141004.8	Nmm	(According to Meyer, with additional 20%)

Bamboo:

Density	ρ_k	641	kg/m³	(Schikhofer, 2015)
	$\rho_{average}$	666	kg/m³	(Schikhofer, 2015)
Embedment strength	$f_{h,0,k}$	46.25456	N/mm²	(Volgens EC5)
	$f_{h,0}$	59.78016	N/mm²	(According to Ehlbeck and Werner)

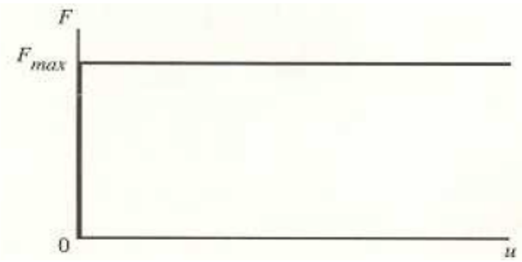
The embedment strength f_h is defined as the maximum stress level at or before 15 mm displacement of the dowel in the timber.
The following graph shows a typical load embedment diagram.



The embedment stress level is determined by measuring the force needed to displace the dowel 15 mm and dividing that force by the dowel diameter and the thickness of the timber member.

$$f_h = \frac{F_{max}}{t * d_0} \quad \text{with:} \quad \begin{aligned} t &= member\ thickness \\ d_0 &= dowel\ diameter \end{aligned}$$

In deriving the resistance through Johansens formulas the Eurocode then assumes the timber (and the dowel) to be an ideal rigid-plastic material. This simplification makes little to no difference in the ultimate resistance of the connection but lets us use a simplified load-embedment diagram:



The embedment strength can now be applied at every displacement of the dowel. This means that f_h can be taken as a constant value regardless of the amount of displacement/rotation of the fastener. The correctness of such a simplification in bamboo connections will need to be studied by doing embedment tests.
To study the posibility of calculating laminated bamboo connections by means of Eurocode 5 and to verify that the calculated capacity corresponds to the actual capacity and that the behaviour of connections with slotted-in steel plates in laminated bamboo is as predicted by Eurocode 5, test pieces will be made using only one dowel, of which the dowel diameter and placement are kept constant, and a varying member thickness. The member thicknesses that shall be tested follow from the following calculation:

The thickness of the bamboo beam depends on the failure mode we want to observe (Murty, 2005):

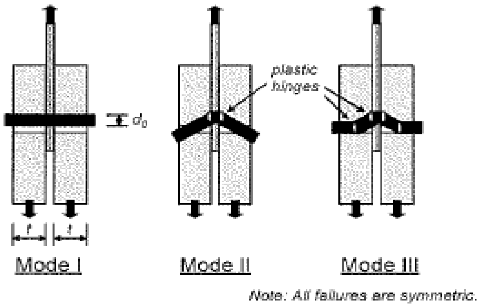


Figure 13. EYM modes for a wood – steel plate – wood connection

$$F_y = \min \begin{cases} t d_o f_h & \text{for } t < \sqrt{\dfrac{2M_y}{d_o f_h}} & \text{Mode I} \quad (1) \\ \left(\sqrt{2 + \dfrac{4M_y}{t^2 d_o f_h}} - 1\right) t d_o f_h & \text{for } \sqrt{\dfrac{2M_y}{d_o f_h}} \le t < \sqrt{\dfrac{16M_y}{d_o f_h}} & \text{Mode II} \quad (2) \\ \sqrt{4M_y d_o f_h} & \text{for } t \ge \sqrt{\dfrac{16M_y}{d_o f_h}} & \text{Mode III} \quad (3) \end{cases}$$

According to EC5:

	t <	18.78	mm
18.78	≤ t ≥	53.11	mm
53.11	≤ t		mm

Theoretical boundaries,
According to Ehlbeck and Werner

	t <	16.88	mm
16.88	≤ t ≥	47.75	mm
47.75	≤ t		mm

Theoretical boundaries,
According to Ehlbeck and Werner plus 20%

	t <	19.83	mm
19.83	≤ t ≤	56.08	mm
56.08	≤ t		mm

For test piece design the theoretical value of the thicknesses will be used. Tests shall be conducted at thicknesses that are a multidude of 6mm. This in consideration of the production process that produces lamination strips of an average thickness of 6mm. With the calculated member thicknesses for each failure mode to occur the expectancy for the tested thicknesses will be:

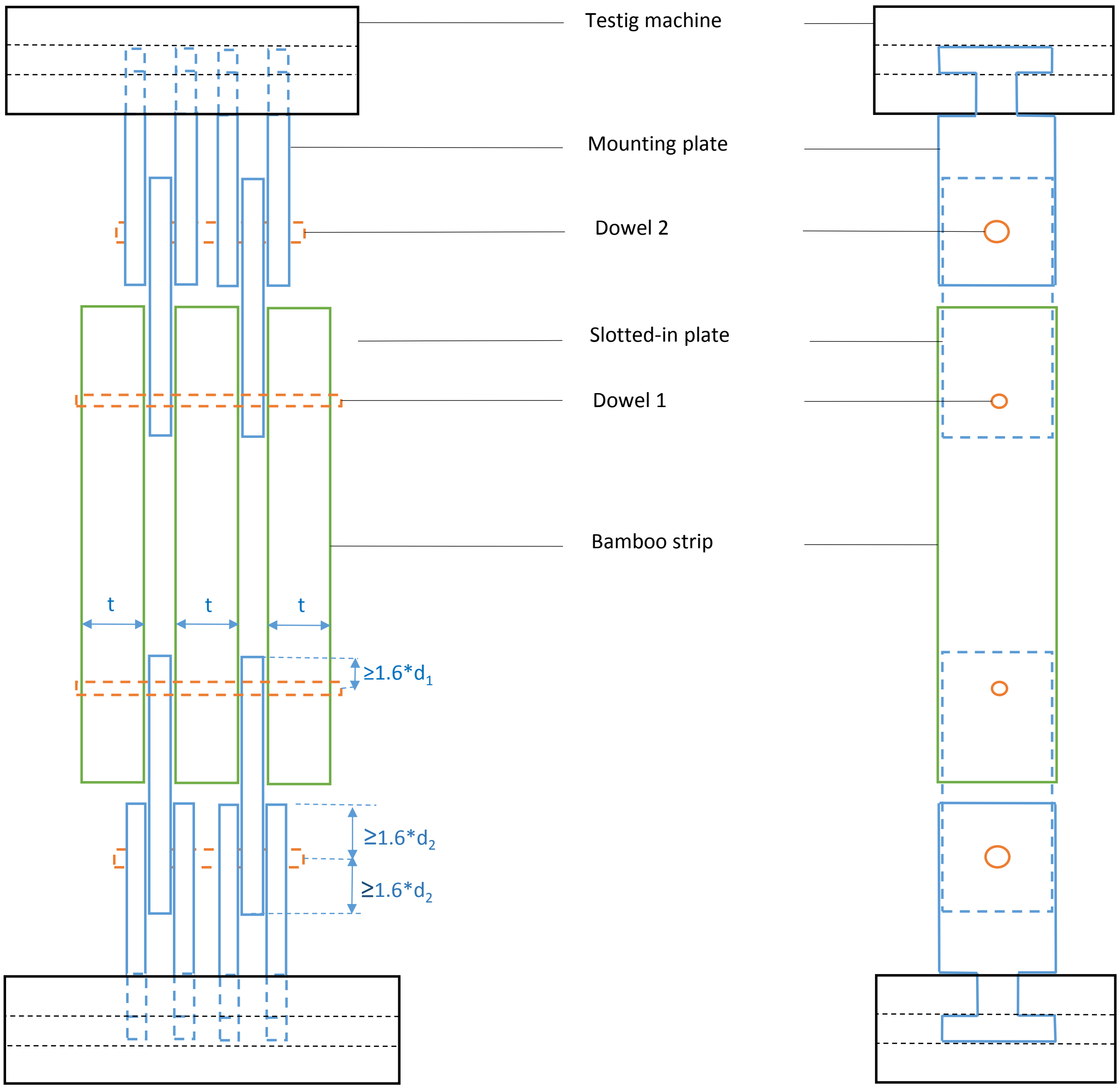
Thickness 't'		expected failure mode:
12	mm	mode 1
36	mm	mode 2
72	mm	mode 3

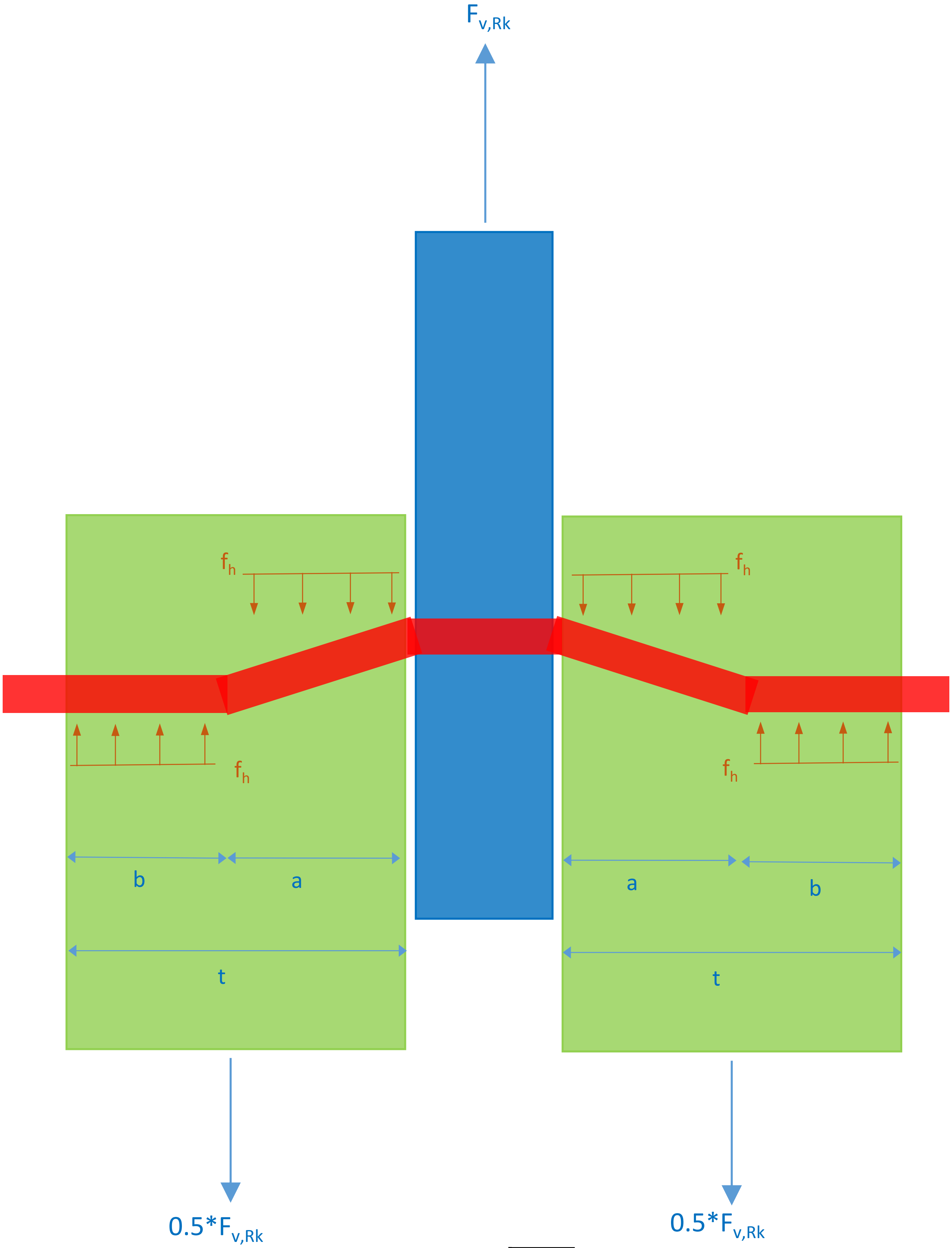
For the variant with one slotted-in plate all the above member thicknesses will be tested. After that, a comparison can be made with the design rules from EC5. To observe the behaviour of connections with multiple slotted plates the member thicknesses of the middle and outer members shall be varied for a variant with 2 slotted-in plates and the occuring failure modes will be observed. The thickness of the middle member is kept constant at two different values (one thickness that ensures mode 1 to occur and one thickness for failure mode 3).
To account for (natural occurring) variance in material properties each test will be performed five times.

Connections will be made using one and two slotted-in steel plates. Steel grade:

355 N/mm²	yield
510 N/mm²	ultimate

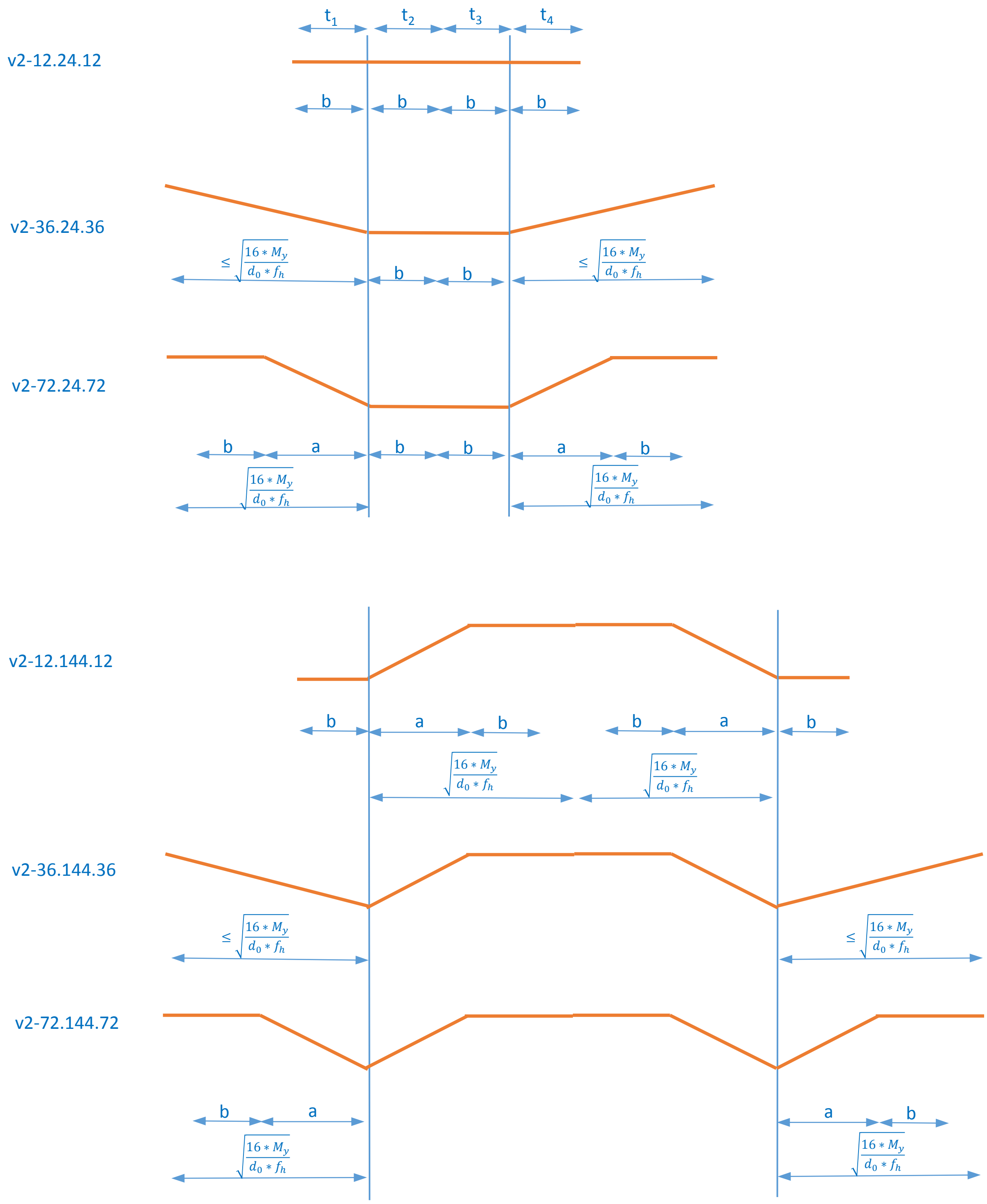
The test setup will be as follows:





$$t > a + b \;\rightarrow with: \quad a = \sqrt{\frac{4 * M_y}{f_h * d_1}} \quad b = \sqrt{\frac{2 * M_y}{f_h * d_1}}$$

The expected failure mechanisms for the 2 slotted variants are as follows:



The codename for a variant has the following explenation:

variant 'n' plates - thickness t_1. middle member thicnkess. thickness t_4

The theoretical maximum resistance $F_{v,Rk}$ is given in the following tables:

According to EC5:

1 slotted-in plate

	Slotted plates	Shear planes	Dowel 1 diameter	M_y	f_h	t	a	b
			[mm]	[Nmm]	[N/mm²]	[mm]	[mm]	[mm]
v1-12.12	1	2	12	97850	46.3	12	27	19
v1-36.36	1	2	12	97850	46.3	36	27	19
v1-72.72	1	2	12	97850	46.3	72	27	19

2 slotted-in plates

	Slotted plates	Shear planes	t_1	t_2	t_3	t_4	Load from t_1	Load from t_2
			[mm]	[mm]	[mm]	[mm]	[kN]	[kN]
v2-12.24.12	2	4	12	12	12	12	6.7	6.7
v2-36.24.36	2	4	36	12	12	36	11.9	6.7
v2-72.24.72	2	4	72	12	12	72	14.7	6.7
v2-12.144.12	2	4	12	72	72	12	6.7	14.7
v2-36.144.36	2	4	36	72	72	36	11.9	14.7
v2-72.144.72	2	4	72	72	72	72	14.7	14.7

Theoretical resistance (embedment according to Ehlbeck and Werner):

1 slotted-in plate

	Slotted plates	Shear planes	Dowel 1 diameter	M_y	f_h	t	a	b
			[mm]	[Nmm]	[N/mm²]	[mm]	[mm]	[mm]
v1-12.12	1	2	12	102240	59.8	12	24	17
v1-36.36	1	2	12	102240	59.8	36	24	17
v1-72.72	1	2	12	102240	59.8	72	24	17

2 slotted-in plates

	Slotted plates	Shear planes	t_1	t_2	t_3	t_4	Load from t_1	Load from t_2
			[mm]	[mm]	[mm]	[mm]	[kN]	[kN]
v2-12.24.12	2	4	12	12	12	12	8.6	8.6
v2-36.24.36	2	4	36	12	12	36	14.5	8.6
v2-72.24.72	2	4	72	12	12	72	17.1	8.6
v2-12.144.12	2	4	12	72	72	12	8.6	17.1
v2-36.144.36	2	4	36	72	72	36	14.5	17.1
v2-72.144.72	2	4	72	72	72	72	17.1	17.1

With an additional 20%:

1 slotted-in plate

	Slotted plates	Shear planes	Dowel 1 diameter	M_y	f_h	t	a	b
			[mm]	[Nmm]	[N/mm²]	[mm]	[mm]	[mm]
v1-12.12	1	2	12	141005	59.8	12	28	20
v1-36.36	1	2	12	141005	59.8	36	28	20
v1-72.72	1	2	12	141005	59.8	72	28	20

2 slotted-in plates

	Slotted plates	Shear planes	t_1	t_2	t_3	t_4	Load from t_1	Load from t_2
			[mm]	[mm]	[mm]	[mm]	[kN]	[kN]
v2-12.24.12	2	4	12	12	12	12	8.6	8.6
v2-36.24.36	2	4	36	12	12	36	15.9	8.6
v2-72.24.72	2	4	72	12	12	72	20.1	8.6
v2-12.144.12	2	4	12	72	72	12	8.6	20.1
v2-36.144.36	2	4	36	72	72	36	15.9	20.1
v2-72.144.72	2	4	72	72	72	72	20.1	20.1

$F_{v,Rk}$ Mode 1	$F_{v,Rk}$ Mode 2	$F_{v,Rk}$ Mode 3	Dowel shear	Dowel embedment	Slotted plate thickness	Applied slotted plate	Connection thickness
[kN]	[kN]	[kN]	[o.k./n.o.k.]	[o.k./n.o.k.]	[mm]	[mm]	[mm]
13.3	21.7	29.5	o.k.	o.k.	6.40	8.00	32.00
40.0	23.8	29.5	o.k.	o.k.	6.40	8.00	80.00
79.9	36.9	29.5	o.k.	o.k.	6.40	8.00	152.00
			o.k.	n.o.k.			

Load from t_3	Load from t_4	Expected load per slotted plate: plate 1	plate 2	Connection thickness		
[kN]	[kN]	[kN]	[kN]	[mm]		
6.7	6.7	13.3	13.3	64		
6.7	11.9	18.6	18.6	112		
6.7	14.7	21.4	21.4	184		
14.7	6.7	21.4	21.4	184		
14.7	11.9	26.6	26.6	232	Length dowel 1:	6720.00 mm
14.7	14.7	29.5	29.5	304	Two dowels per test piece:	13440.00 mm

$F_{v,Rk}$ Mode 1	$F_{v,Rk}$ Mode 2	$F_{v,Rk}$ Mode 3	Dowel shear	Dowel embedment	Slotted plate thickness	Applied slotted plate	Connection thickness
[kN]	[kN]	[kN]	[o.k./n.o.k.]	[o.k./n.o.k.]	[mm]	[mm]	[mm]
17.2	24.8	34.3	o.k.	o.k.	6.40	8.00	32.00
51.7	29.0	34.3	o.k.	o.k.	6.40	8.00	80.00
103.3	46.8	34.3	o.k.	o.k.	6.88	8.00	152.00
			o.k.	n.o.k.			

Load from t_3	Load from t_4	Expected load per slotted plate: plate 1	plate 2	Connection thickness		
[kN]	[kN]	[kN]	[kN]	[mm]		
8.6	8.6	17.2	17.2	64		
8.6	14.5	23.1	23.1	112		
8.6	17.1	25.7	25.7	184		
17.1	8.6	25.7	25.7	184		
17.1	14.5	31.6	31.6	232	Length dowel 1:	6720.00 mm
17.1	17.1	34.3	34.3	304	Two dowels per test piece:	13440.00 mm

$F_{v,Rk}$ Mode 1	$F_{v,Rk}$ Mode 2	$F_{v,Rk}$ Mode 3	Dowel shear	Dowel embedment	Slotted plate thickness	Applied slotted plate	Connection thickness
[kN]	[kN]	[kN]	[o.k./n.o.k.]	[o.k./n.o.k.]	[mm]	[mm]	
17.2	29.8	40.2	o.k.	o.k.	6.80	8.00	32.00
51.7	31.7	40.2	o.k.	o.k.	6.80	8.00	80.00
103.3	48.2	40.2	o.k.	o.k.	7.45	8.00	152.00
			o.k.	n.o.k.			

Load from t_3	Load from t_4	Expected load per slotted plate: plate 1	plate 2	Connection thickness		
[kN]	[kN]	[kN]	[kN]	[mm]		
8.6	8.6	17.2	17.2	64		
8.6	15.9	24.5	24.5	112		
8.6	20.1	28.7	28.7	184		
20.1	8.6	28.7	28.7	184		
20.1	15.9	36.0	36.0	232	Length dowel 1:	6720.00 mm
20.1	20.1	40.2	40.2	304	Two dowels per test piece:	13440.00 mm

The test pieces will be attached to the testing machine by means of a dowelled connection and steel plates which can be inserted in the grooves of the machine. With dowel 1 being the fastener in the bamboo connection and dowel 2 the fastener for the testing equipment

Dowel 2

Diameter	$ø_{dowel,2}$	16	mm	
Tensile strength	f_u	1000	N/mm²	
Yield stress	f_y	900	N/mm²	
Shear resistance	$F_{v,Rd}$	96.5	kN	(NEN-en 1993-1-1 table 3.10)
Embedment capacity	$F_{b,Rd}$	21.6	kN/mm	(NEN-en 1993-1-1 table 3.10)

The width of the steel plate is determined by MAX(test piece thickness; 2.5*$ø_{dowel,2}$)
This is then rounded up to the nearest standard strip width: 80 mm

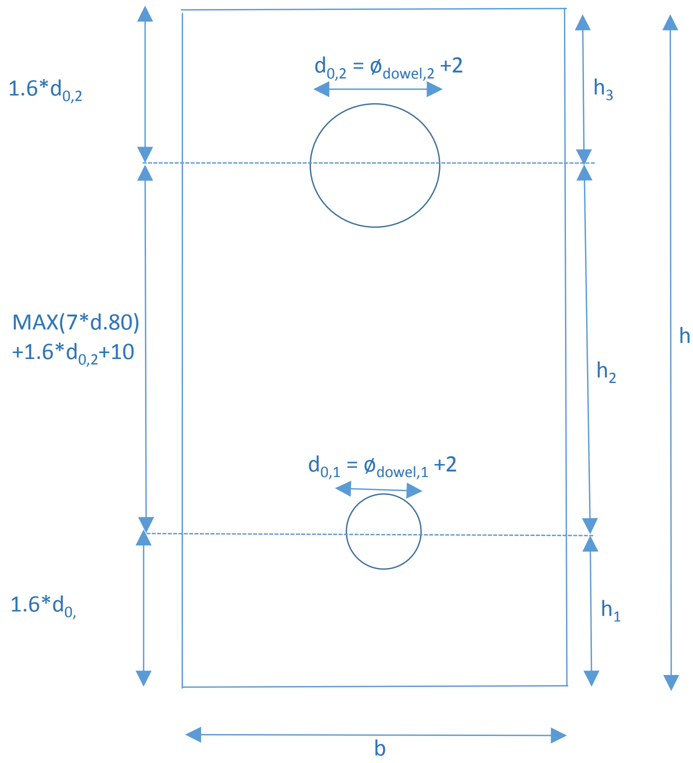
The minimum required plate thickness is the maximum of the following:
The values given are for failure mode 3

$$t_{plate,min} = \begin{cases} \frac{F_{v,Rk}}{\#_{plates} * f_y * w_{plate}} \ (gross\ section) & 1.57\ \text{mm} \\ \frac{F_{v,Rk}}{\#_{plates} * f_u * (w_{plate} - ø_{dowel,2})} \ (net\ section) & 1.23\ \text{mm} \\ 0.7 * \sqrt{\frac{F_{v,Rk} * \gamma_{M0}}{\#_{plates} * f_y}} & 7.45\ \text{mm} \\ \frac{ø_{dowel,1} + 1}{2.5} \quad \text{(NEN 1993 tabe 3.9)} & 5.20\ \text{mm} \\ \frac{ø_{dowel,2} + 1}{2.5} & 6.80\ \text{mm} \end{cases}$$

7.45 mm

The actual size and capacity of the slotted-in plates:

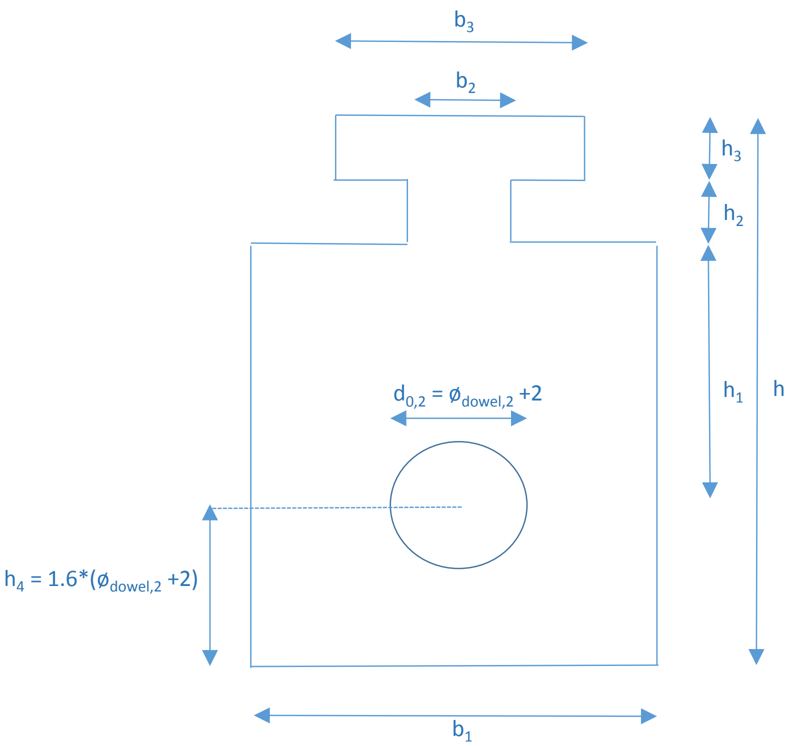
b	80	mm
t	8	mm
h	180	mm
h_1	25	mm
h_2	125	mm
h_3	30	mm
$d_{0,2}$	18	mm
$d_{0,1}$	14	mm



Embedment capacity	$1.5*f_y*t*d_1/\gamma_{M0}$	51.12	kN
Net section	$t*(b-d_2-1)*f_y$	176.08	kN
Plate capacity		51.12	kN

The dimensions of the mounting plate shall be:

b_1	44 mm
b_2	18 mm
b_3	36 mm
h	107 mm
h_1	34 mm
h_2	30 mm
h_3	14 mm
h_4	29 mm
$ø_{dowel,2}$ +2	18 mm



The minumum thickness of this plate is determined by the maximm of the following

The mounting plate properties:	Steel:	355 N/mm²	(yield)
		510 N/mm²	(ultimate)
	$\#_{mounting/slotted-}$	2	

$$t_{plate,min} = \begin{cases} t_{slotted-in\ plate,min} & 7.45\ \text{mm} \\ \dfrac{F_{v,Rk}}{\#_{slotted-in\ plates} * \#\dfrac{mountingplates}{slotted-in\ plates} * f_y * b_2}\ (net\ section\ at\ groove) & 3.15\ \text{mm} \\ ,\dfrac{F_{v,Rk}}{\#_{slotted-in\ plates} * \#\dfrac{mountingplates}{slotted-in\ plates} * \dfrac{f_y}{\sqrt{3}} * 2 * h_3}\ (shear\ at\ groove) & 3.51\ \text{mm} \end{cases}$$

7.45 mm

Through communication with another ongoing research at TUDelft is it decided that the mounting plates will be made as thick as possible. This way the plates can also be used for other research and be kept as applications for the testing equipment. The maximum possible thickness of the plates that fits into the test pieces of this research is equal to the thickness of the smallest lamella (24 mm).

$t_{mountingplates,applied}$: 12.00 mm

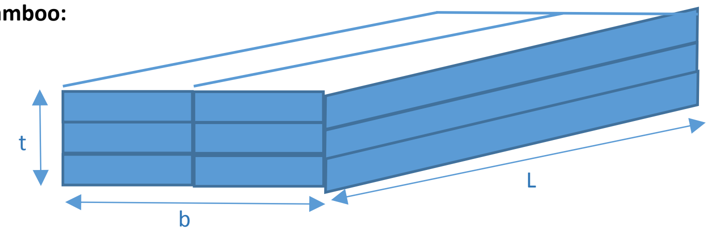
With this applied thickness the actual capacity of the mounting plate will be a minimum of the following:

Embedment capacity	$1.5*f_y*t*d/\gamma_{M0}$	102.24 kN
Plate shear failure	$2*h_3*t*f_y$/SQRT(3)	68.87 kN
Net section dowel	$t*(b-d_2-2)*f_y$	110.76 kN
Net section plate	b_2*t*f_y	76.68 kN
Plate capacity		68.87 kN

Since always two mounting plates will be used per slotted-in plate, the calculated capacity is now about equal to the capacity of the testing apparatus (250 kN). In case of two slotted-in plates per connection, of course.

The testing equipment to be made is as follows:

Bamboo:



#	t [mm]	b [mm]	L [mm]
30	12	72	318
15	24	72	318
30	36	72	318
30	72	72	318
15	144	72	318

Slotted-in plates:
The calculated plate capacity is more than needed. As a result the plates can be reused. By reusing the plates only one set of slotted-in plates will suffice. This results in a total of 4 plates (4 plates per variant of 2 slotted plates). A detailed drawing of the plates is added to this document.

Mounting plates:

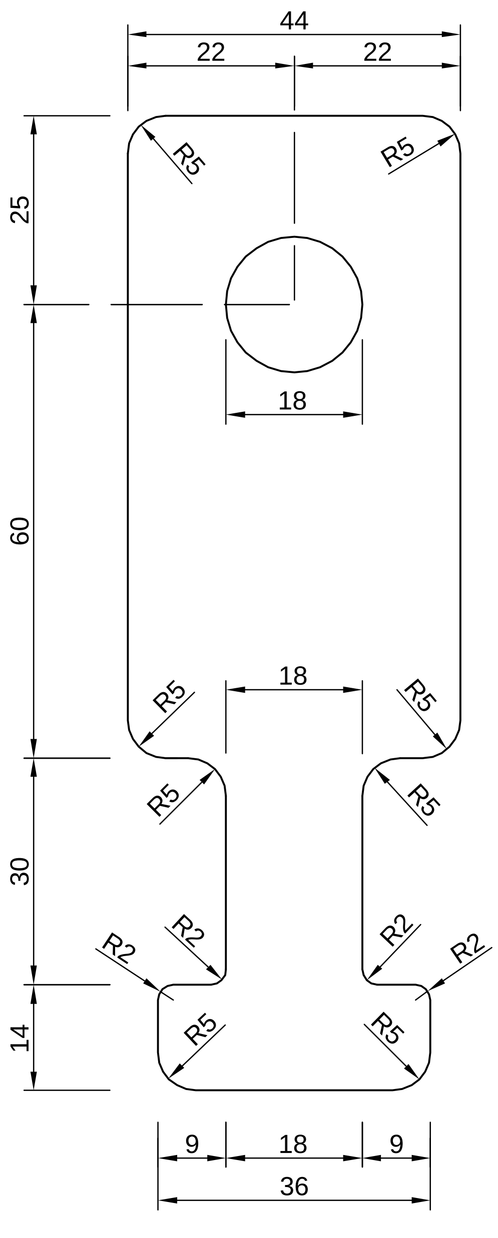
The calculated capacity of the mounting plates is more than needed for the connection tests. As a result, the same mounting plates can be used for all tests. A total of 8 mounting plates will thus suffice (2 mounting plates per slotted-in plate and a maximum of 2 slotted-in plates per test connection). A detailed drawing of the necessary mounting plates is added to this document.

Dowel 1:

#	ø [mm]	fy [N/mm²]	fu [N/mm²]	L_{min} [mm]	$L_{practical}$ [mm]	
10	12	355	510	32	50	
10	12	355	510	80	100	
10	12	355	510	152	200	
10	12	355	510	64	100	
10	12	355	510	112	150	
10	12	355	510	184	200	
10	12	355	510	184	200	
10	12	355	510	232	250	
10	12	355	510	304	350	
				Total length:	16000	mm

Dowel 2:
The calculated capacity of the dowel exceeds the estimated capacity of the connection. This dowel is to be reused for every test in the same manner as the mounting plates. Two dowels are needed to attach a test piece to the testing apparatus.

#	ø [mm]	fy [N/mm²]	fu [N/mm²]	L_{shaft} [mm]
2	16	900	1000	184

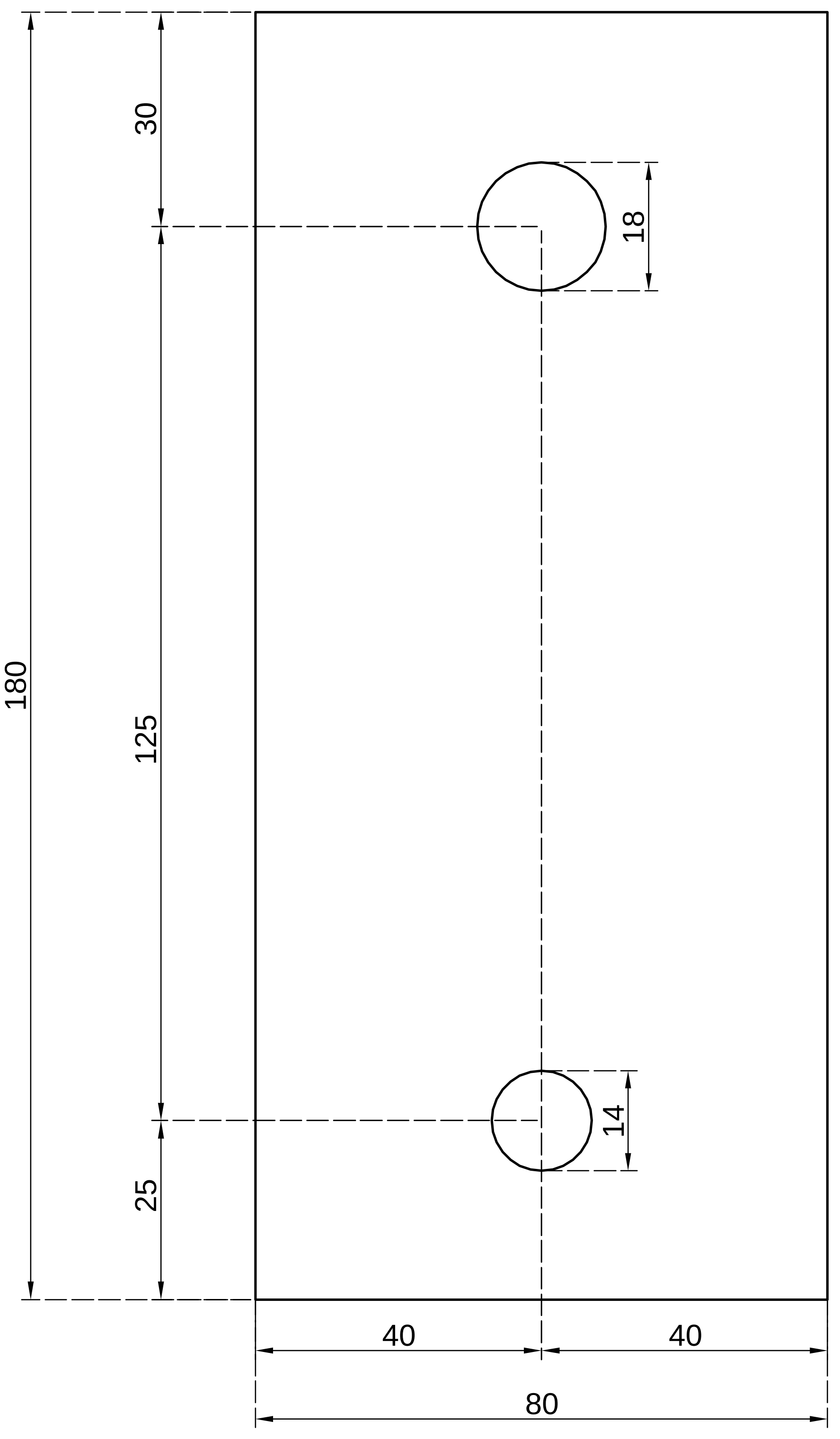


Oplage: 8 stuks
Staalgraad: S355
Plaatdikte: 12mm

Maatvoering in mm, tenzij anders vermeld

Afstudeeropdracht bamboe
Mounting plate tekening

Door:	Jules Debije	Schaal:	1:1
In opdracht:	TUDelft	Papier:	A4
Datum:	04-04-2016	Blad:	1 van 1



Oplage: 8 stuks
Staalgraad: S355
Plaatdikte: 8mm

Maatvoering in mm, tenzij anders vermeld

Afstudeeropdracht bamboe
Slotted-in plate tekening

Door:	Jules Debije	Schaal:	1:1
In opdracht:	TUDelft	Papier:	A4
Datum:	04-04-2016	Blad:	1 van 1