LMDC Toulouse - Tarbes
INSA
QUATERNION DESIGN & RESEARCH
TERRELL
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UNION EUROPÉENNE
La Région Occitanie Pyrénées - Méditerranée
Projet cofinancé par le Fonds Européen de Développement Régional

Timber Gridshell Gerboise

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❑ Literature review

- Numerical analysis.
- Gridshell Shape design.
- Material properties.

1. • Lack of knowledge of experimental tests.
2. • Details of mechanical behavior of connections are missing.
3. • Test protocols are missing.

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❑ Eurocode 5

Section 8: Connections with metal fasteners

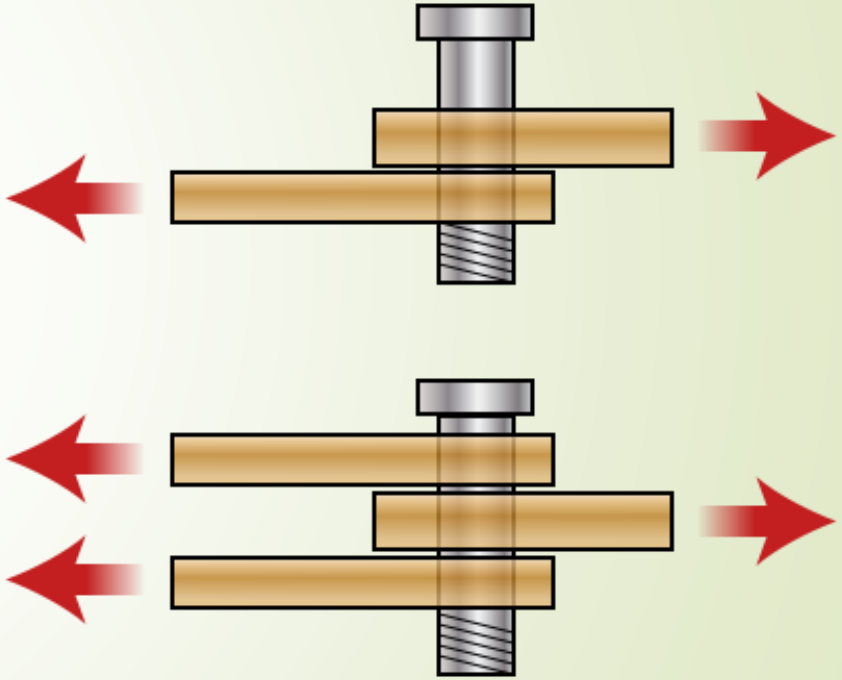
Mechanical connections with:

Dowel type fasteners

- Nails, staples,screws and bolts

Connectors

- Shear plates - Split-rings



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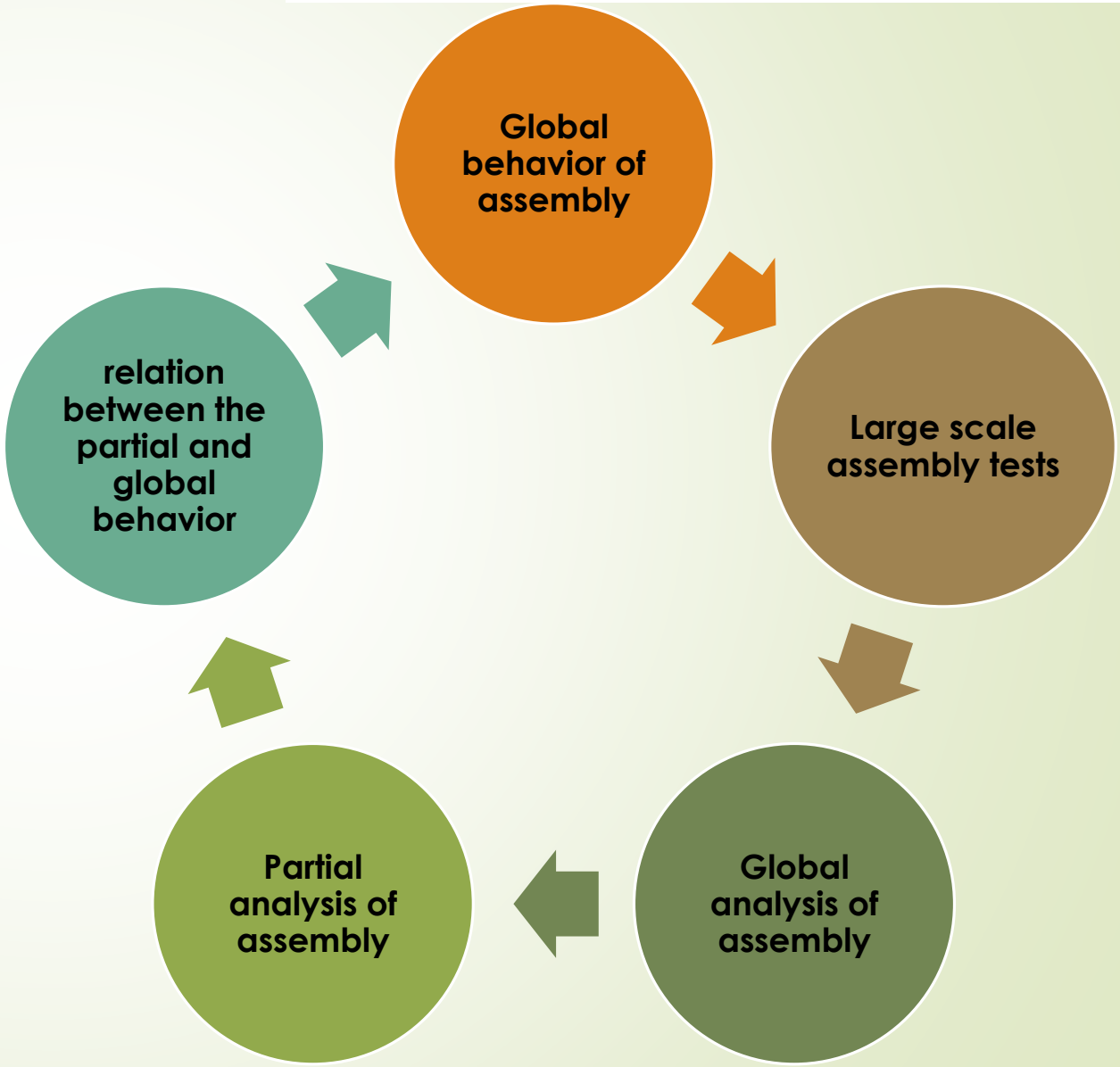
❑ Proposed plan

Global behavior of assembly

Partial behavior of assembly



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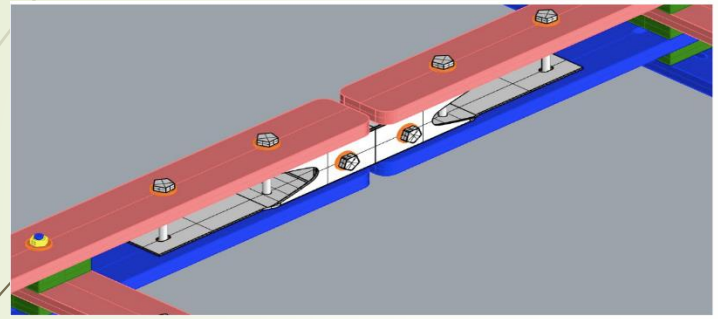
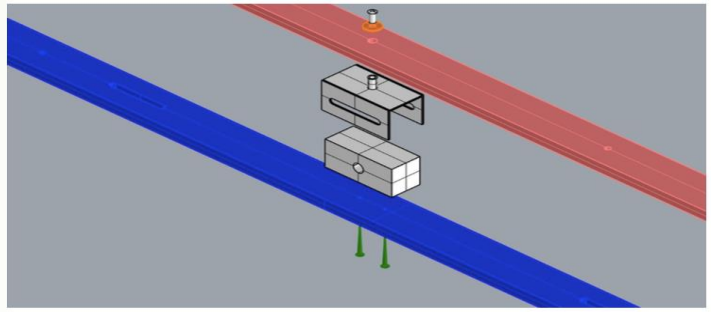
❑ Starting point





- ✓ Flexural behaviour.
- ✓ Less complexity.
- ✓ Proved the required function yesterday.

- More complicated as starting point.
- Manual fixation system.
- Friction between bolts and steel plate.

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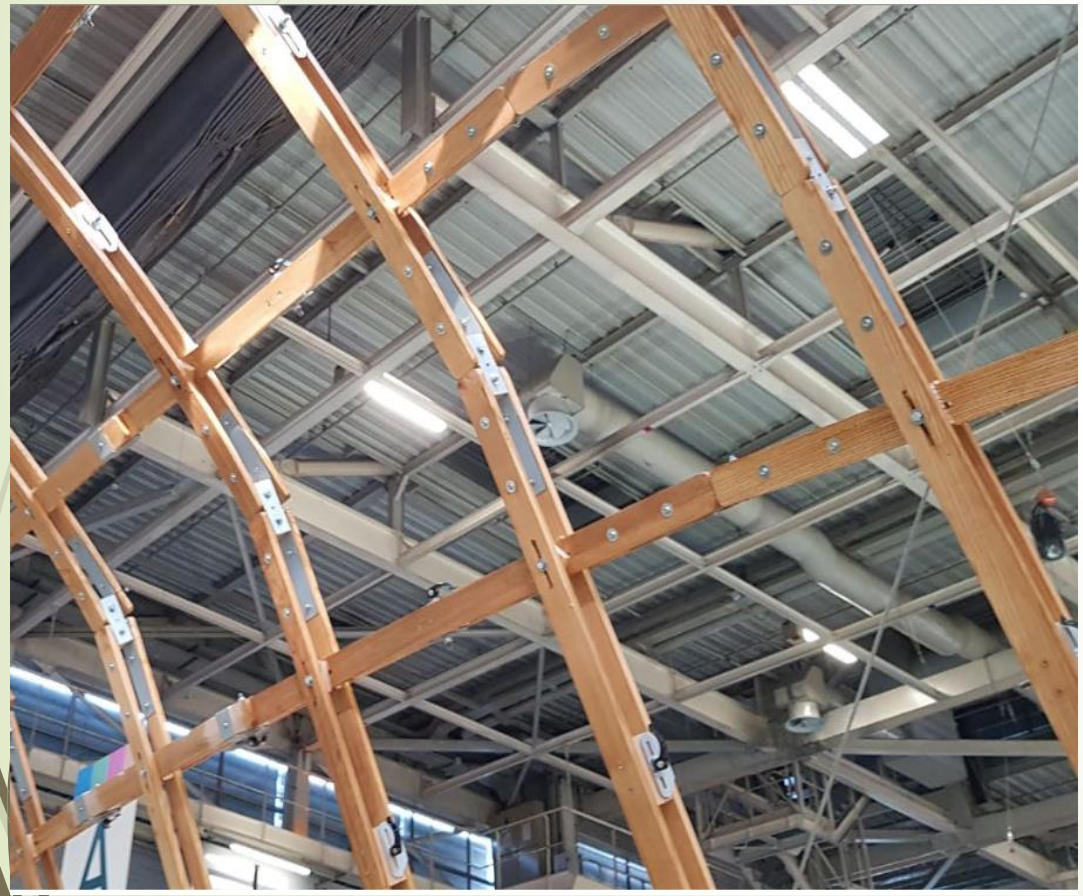
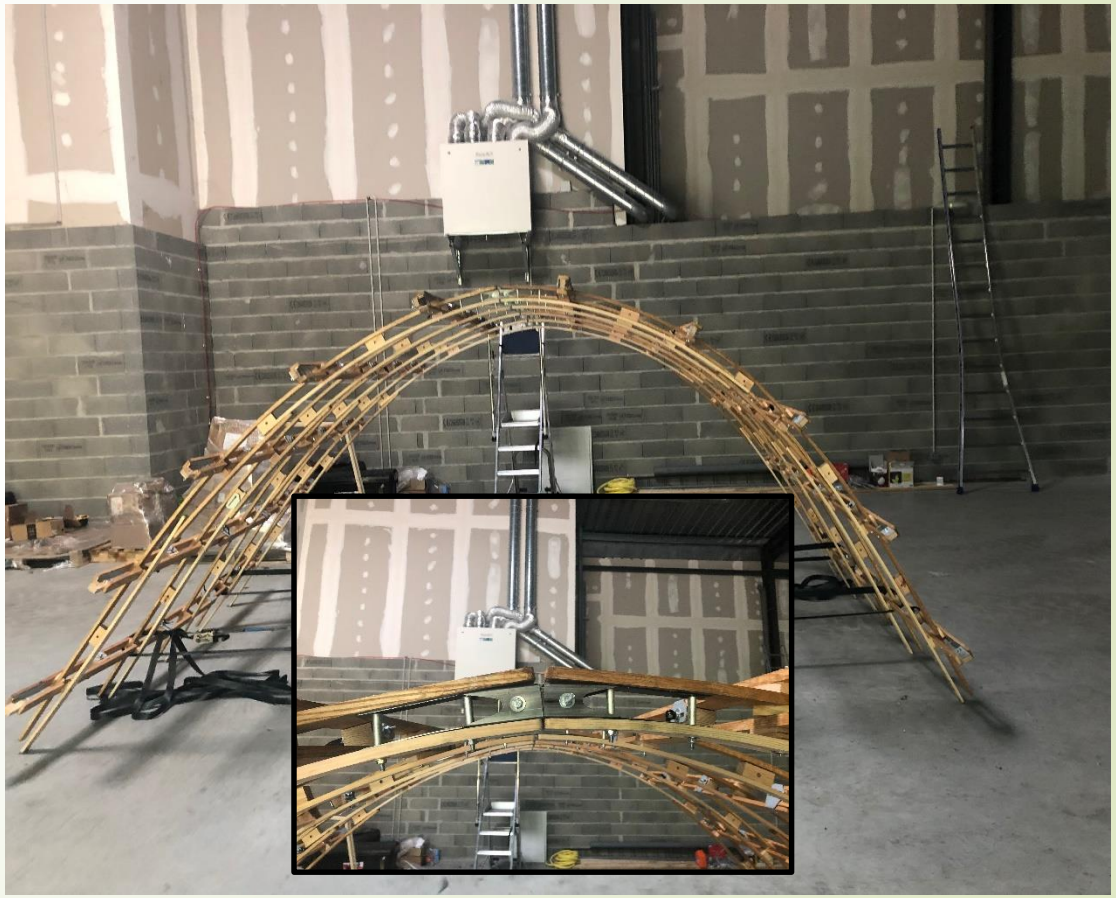
❑ Starting point





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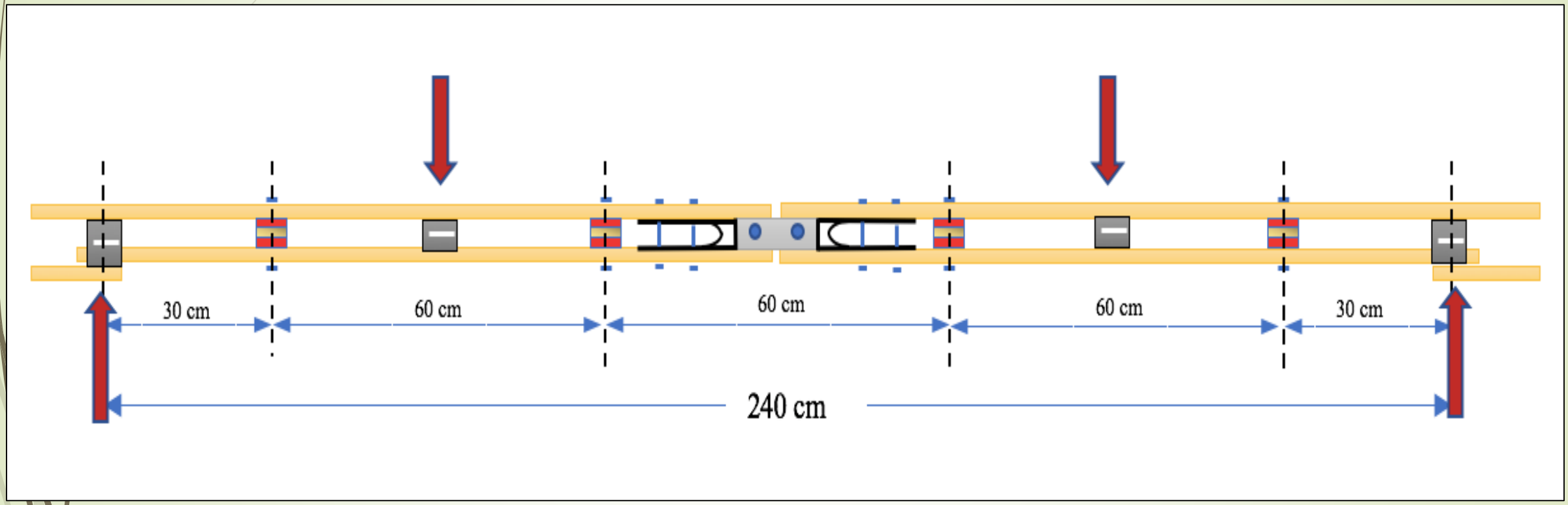
❑ 4 points flexural test



Global behaviour - strength – modes of failure.

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❑ 4 points flexural test

- ✓ Maximum length 2.8 m.
- ✓ Samples for machine calibration.
- ✓ Samples of real assembly.
- ✓ Availability of using the machine:

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❑ 4 points flexural test

- Test protocol
- Preliminary calibration tests

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❑ Previous

❖ Theoretical calculations

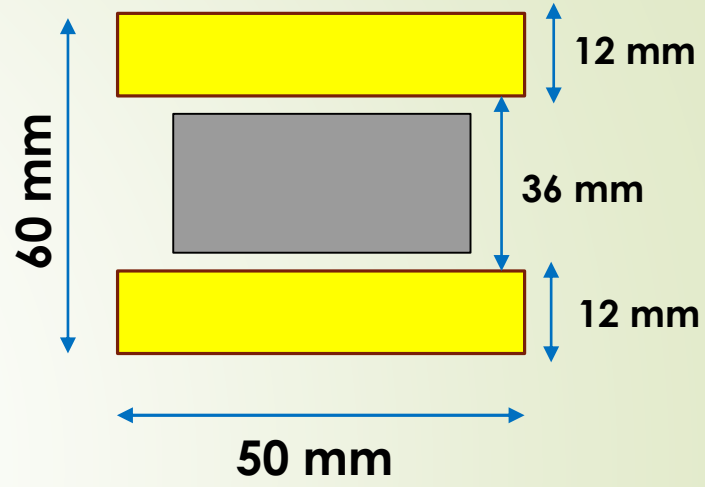
Moment of inertia for beam section

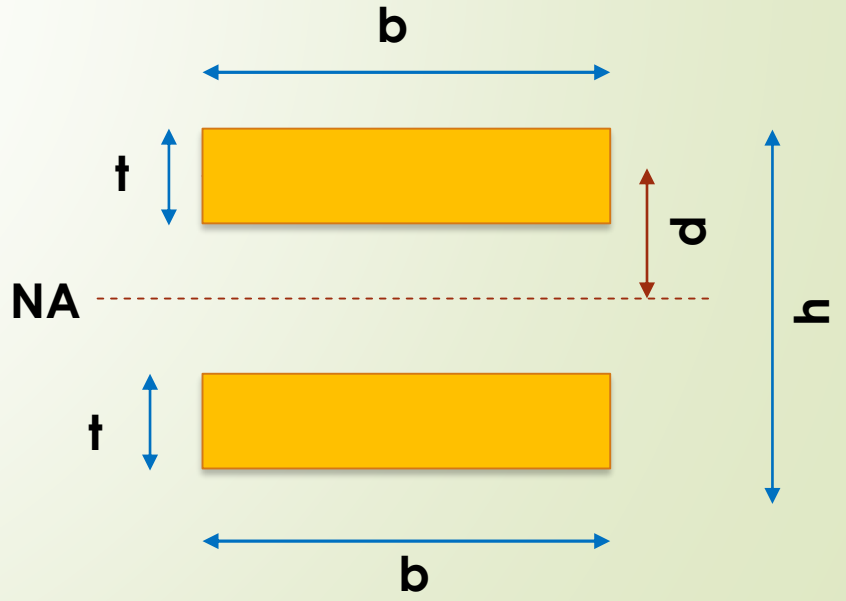
$$I = 2 \times \frac{b t^3}{12} + 2 \times b \times t\left(\frac{h}{2} - \frac{t}{2}\right)^2$$

$$I = 2 \times \frac{5\,(1.2)^3}{12} + \frac{5 \times 1.2}{2}(6 - 1.2)^2$$

$$= 1.44 + 69 \text{ cm}^4$$

$$= 70.5 \text{ cm}^4$$





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Maximum applied force calculations

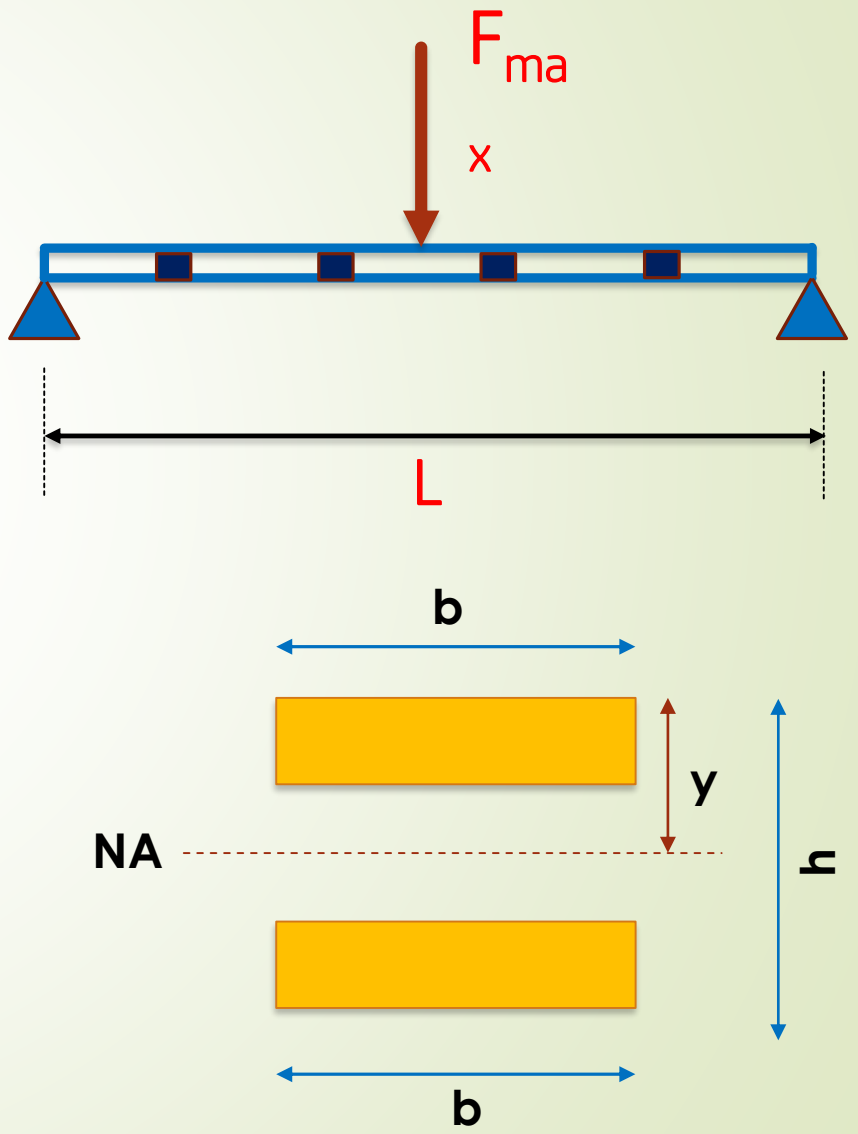
$$M_{max} = \frac{F_{max} \; L}{4}$$

$$\sigma_{max} = \frac{My}{I} \quad , \quad y = h/2 \quad then$$

$$F_{max} = \frac{8 \times \sigma \times I}{L \times h}$$

σ = 40 Mpa , beam length L = 3.35 m , h= 6 cm

$$F_{max} = \frac{8 \times 4000 \times 70.5}{335 \times 6} = 1114 \text{ N}$$



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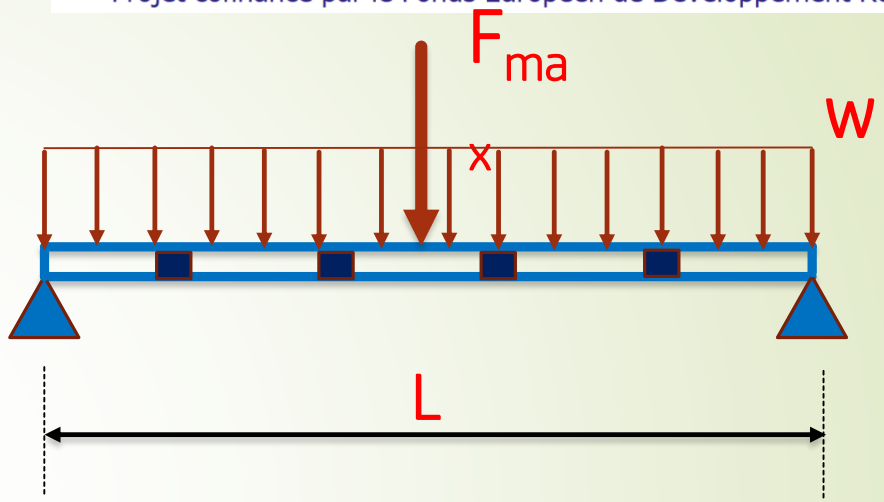
❖ Experimental results

Experimental deflection

E = 10 GPa , L = 2.82 m , P = 30 N



$$\delta = \frac{FL^3}{48\,EI}$$ **Point load**

$$\delta = \frac{5\,wL^4}{384\,EI}$$ **Distributed load**

$$\delta_{total} = \frac{FL^3}{48\,EI} + \frac{5\,wL^4}{384\,EI}$$

$$I_{total} = \frac{FL^3}{48\,E\delta} + \frac{5\,wL^4}{384\,E\delta}$$

Beam	(1)	(2)	(3)	(4)	(5)
Weight(kg)	4.3	3.98	4.92	4.7	4.3
load (N/m)	12.6	11.7	14.4	13.8	12.6
δ exp 10^{-3} m	5.37	13.5	11	39.5	48
Ineria exp 10^{-8} m4	**44.04**	**7.13**	**10.78**	**2.87**	**2.16**

Note: Only beam number (1) loaded with concentrated load, others with only beam weight.

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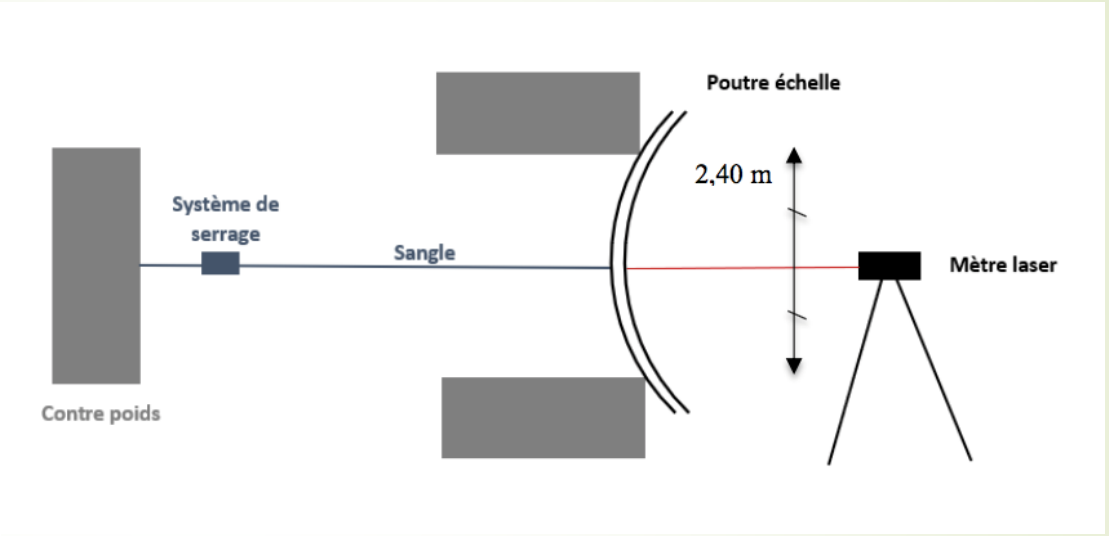
❖ Experimental results

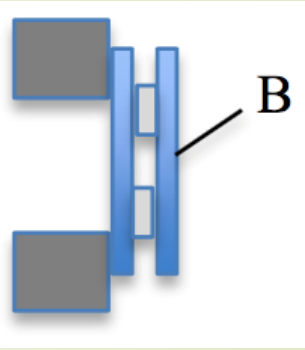
3 points flexural tests

$$\delta = \frac{FL^3}{48\,EI}$$ Point load

$$\delta = \frac{5\,wL^4}{384\,EI}$$ Distributed load

$$\delta_{total} = \frac{FL^3}{48\,EI} + \frac{5\,wL^4}{384\,EI}$$





Beam	(1)	(2)	(3)	(4)	(5)
δ intial (cm)	4.6	4.4	2.2	5	4.7
δ final (cm)	**48**	**26**	**31**	**70**	**50**

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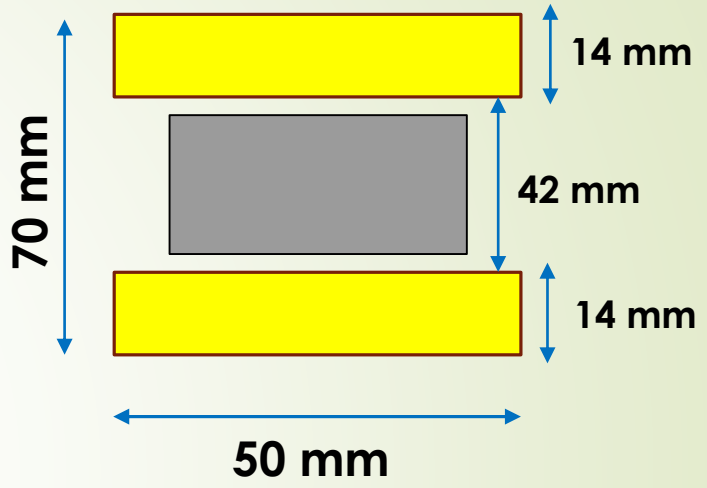
❑ Calculation of the prelimanry tests

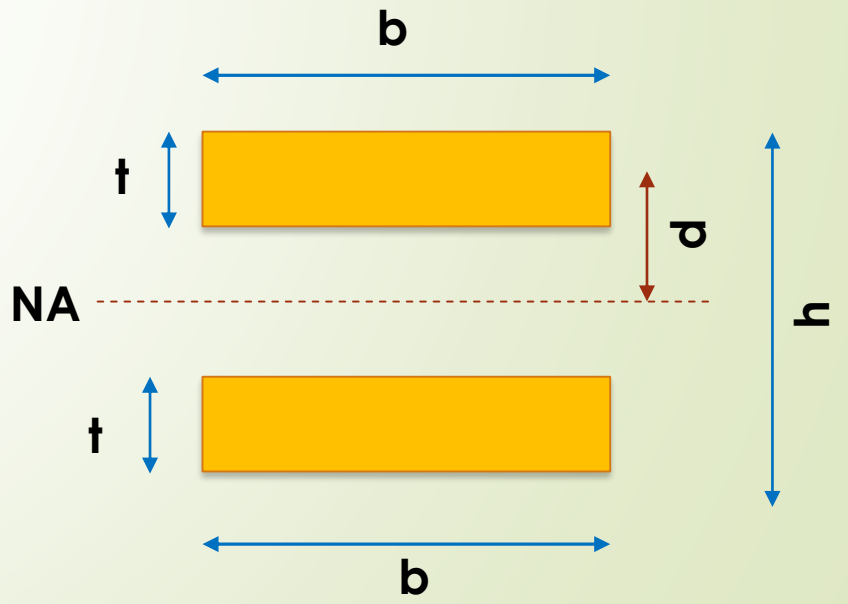
Moment of inertia for beam section

$$I = 2 \times \frac{b t^3}{12} + 2 \times b \times t\left(\frac{h}{2} - \frac{t}{2}\right)^2$$

$$I = 2 \times \frac{5\ (1.4)^3}{12} + \frac{5\ x\ 1.4}{2}(7 - 1.4)^2$$

$$= 85\ cm^4$$





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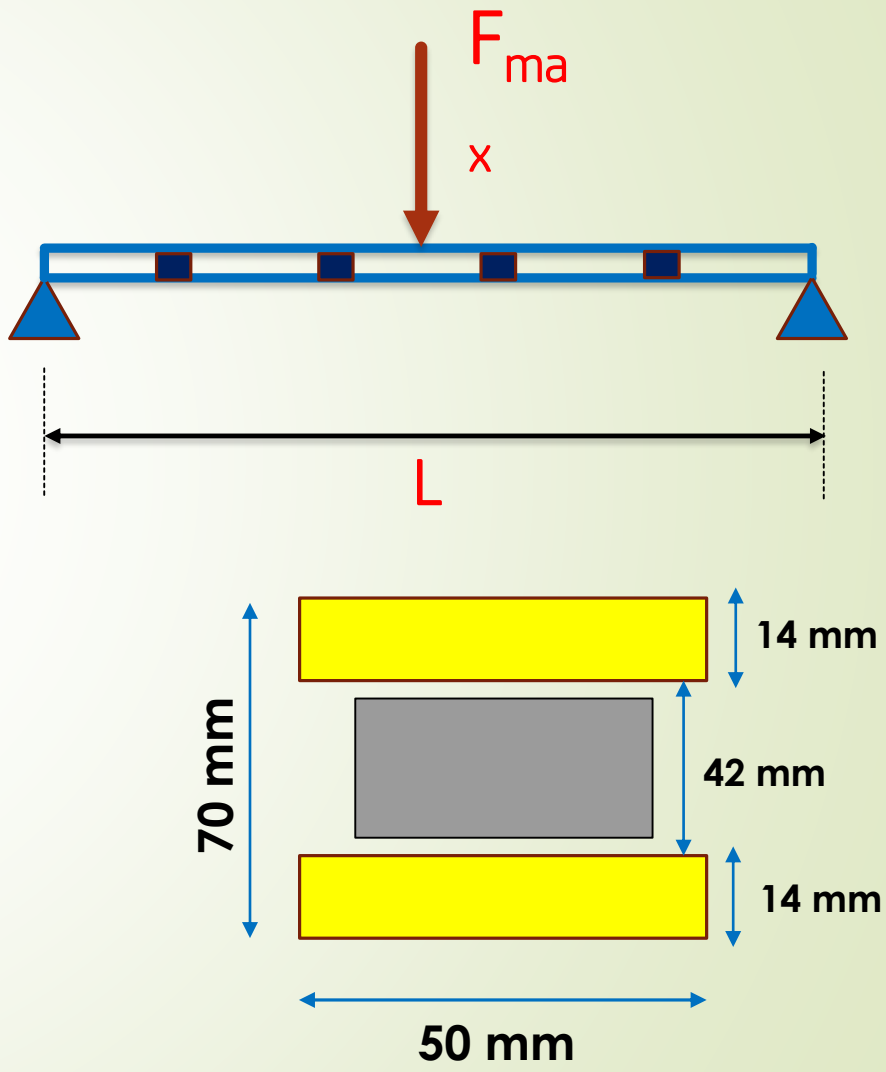
❑ Maximum force

$$F_{max} = \frac{8 \times \sigma \times I}{L \times h}$$

σ = 40 Mpa , beam length L = 2.4 m , h= 7 cm

$$F_{max} = \frac{8 \times 4000 \times 70.5}{240 \times 7} = 1619 \text{ N}$$



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Set up of the preliminary tests

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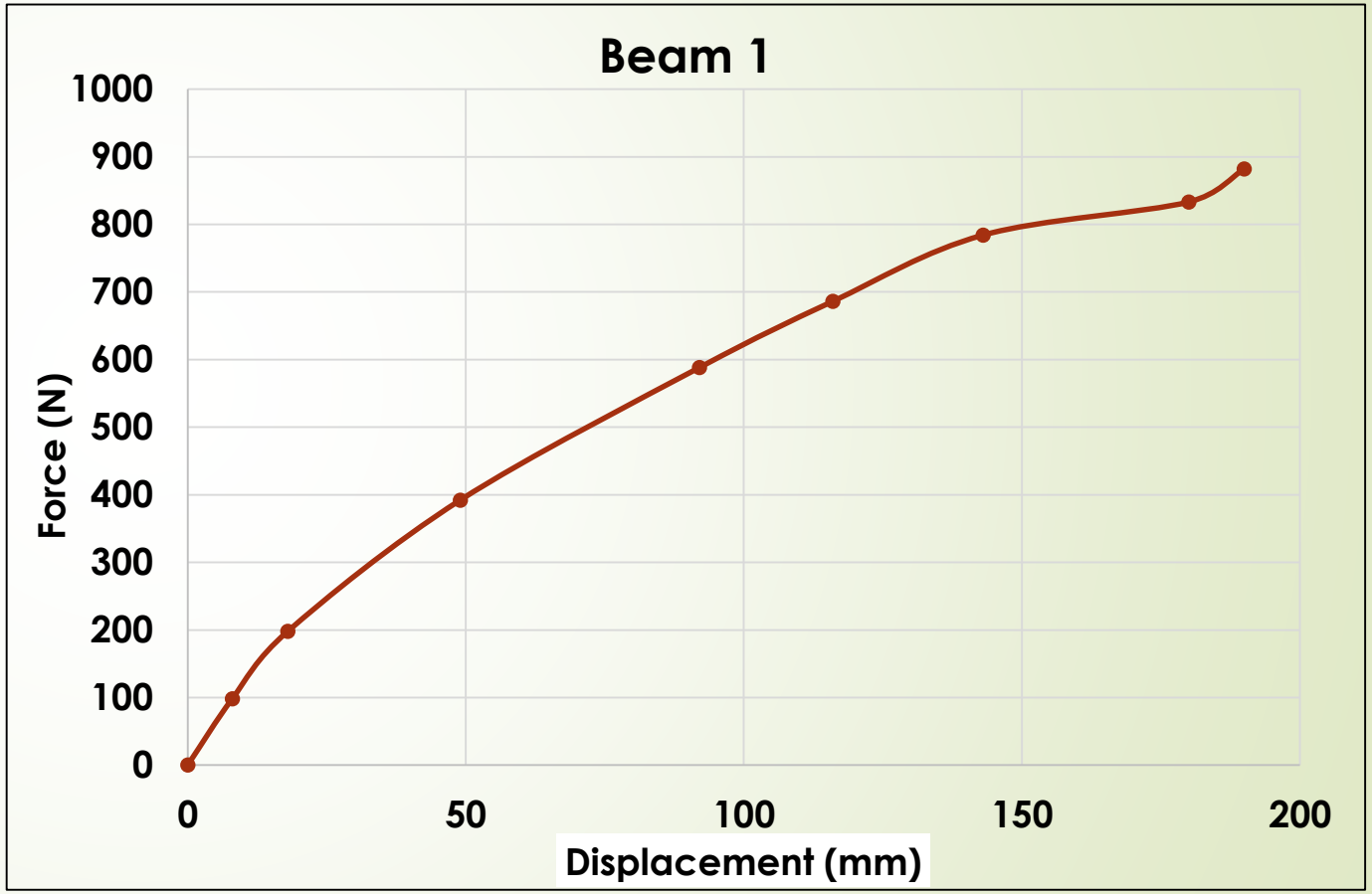
❑ test (1)



Mode of failure (Buckling)

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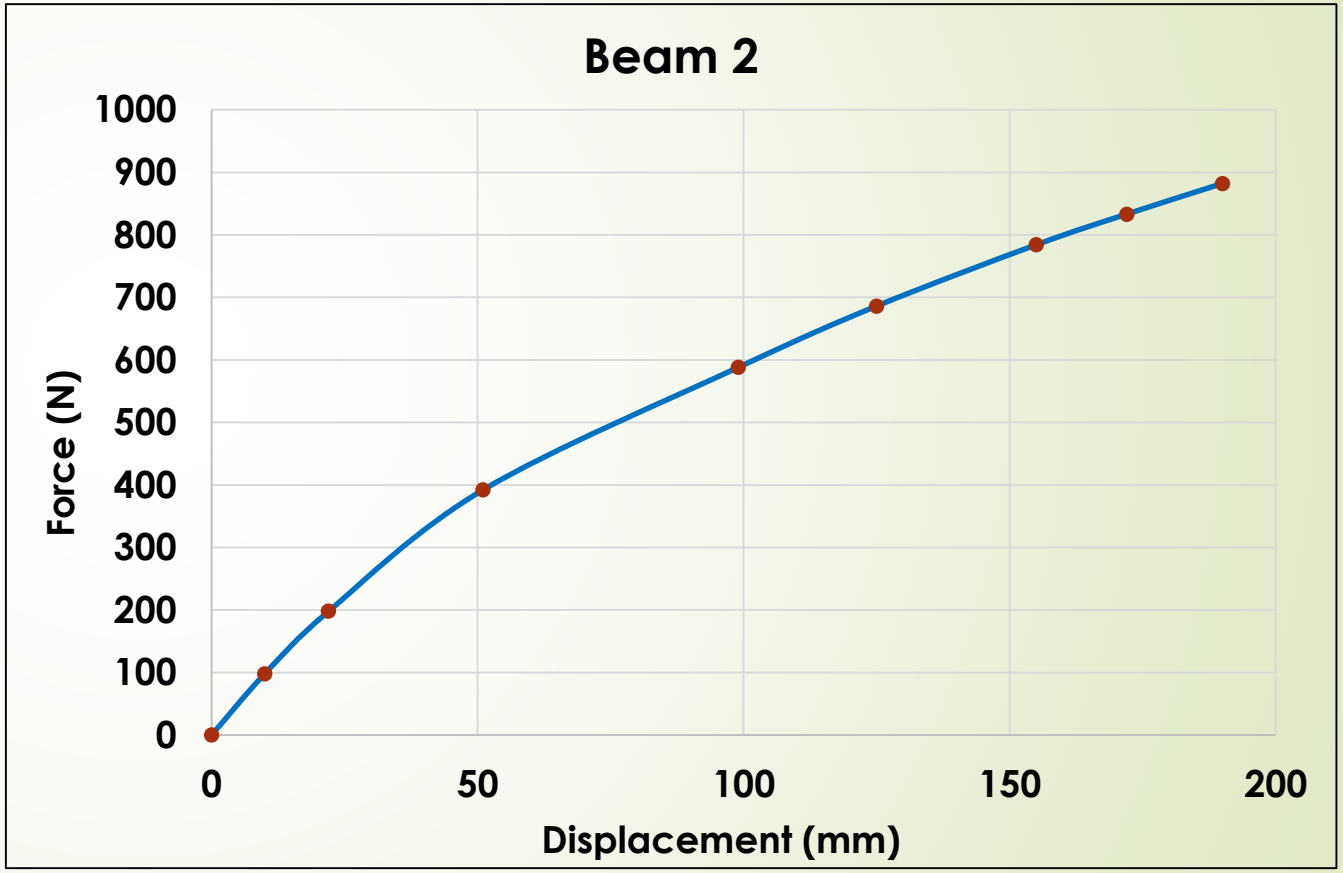
❑ Test (2)



Mode of failure (Support failure)

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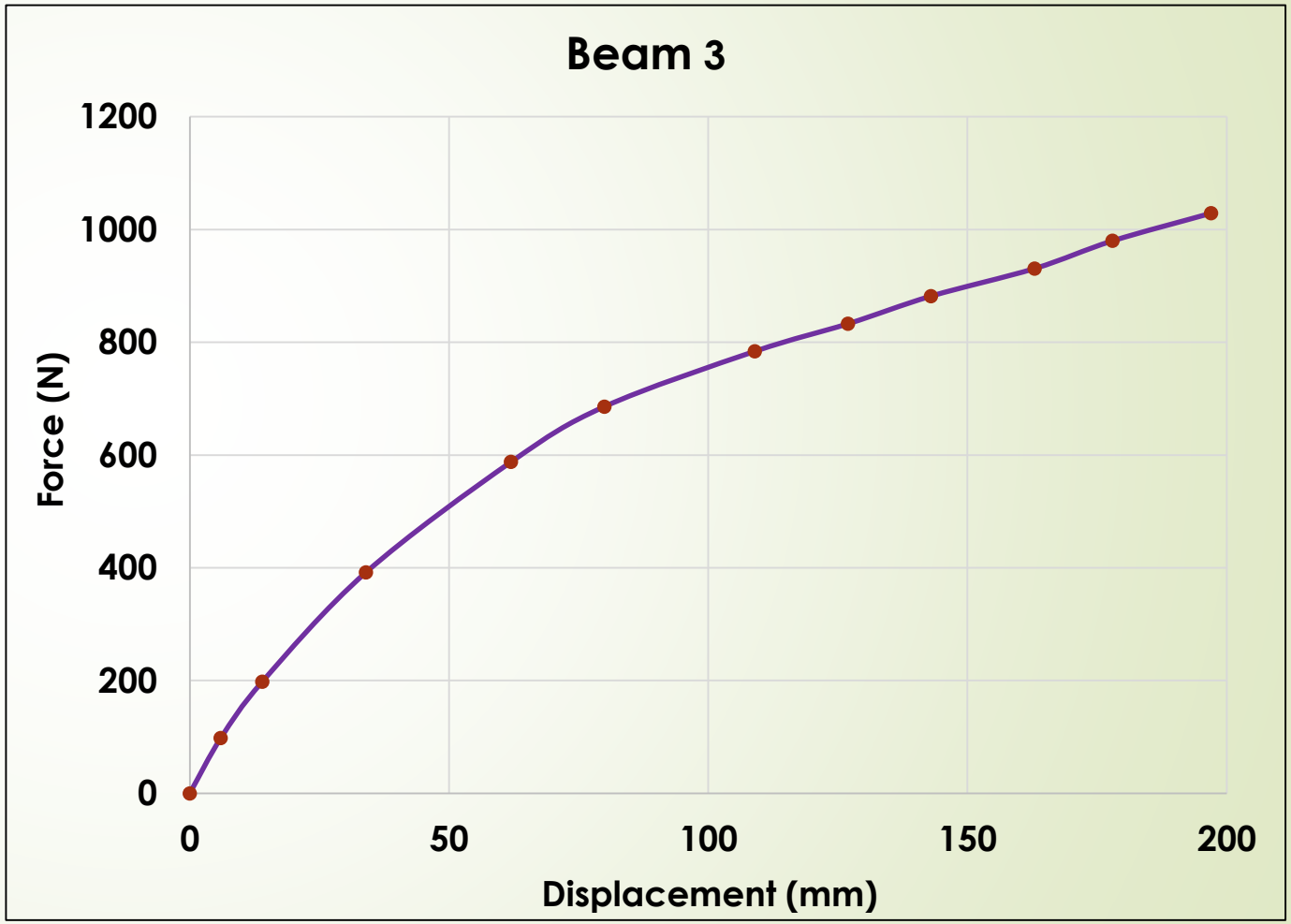
❑ Test (3)

Failure at point of load action



After strengthening the support

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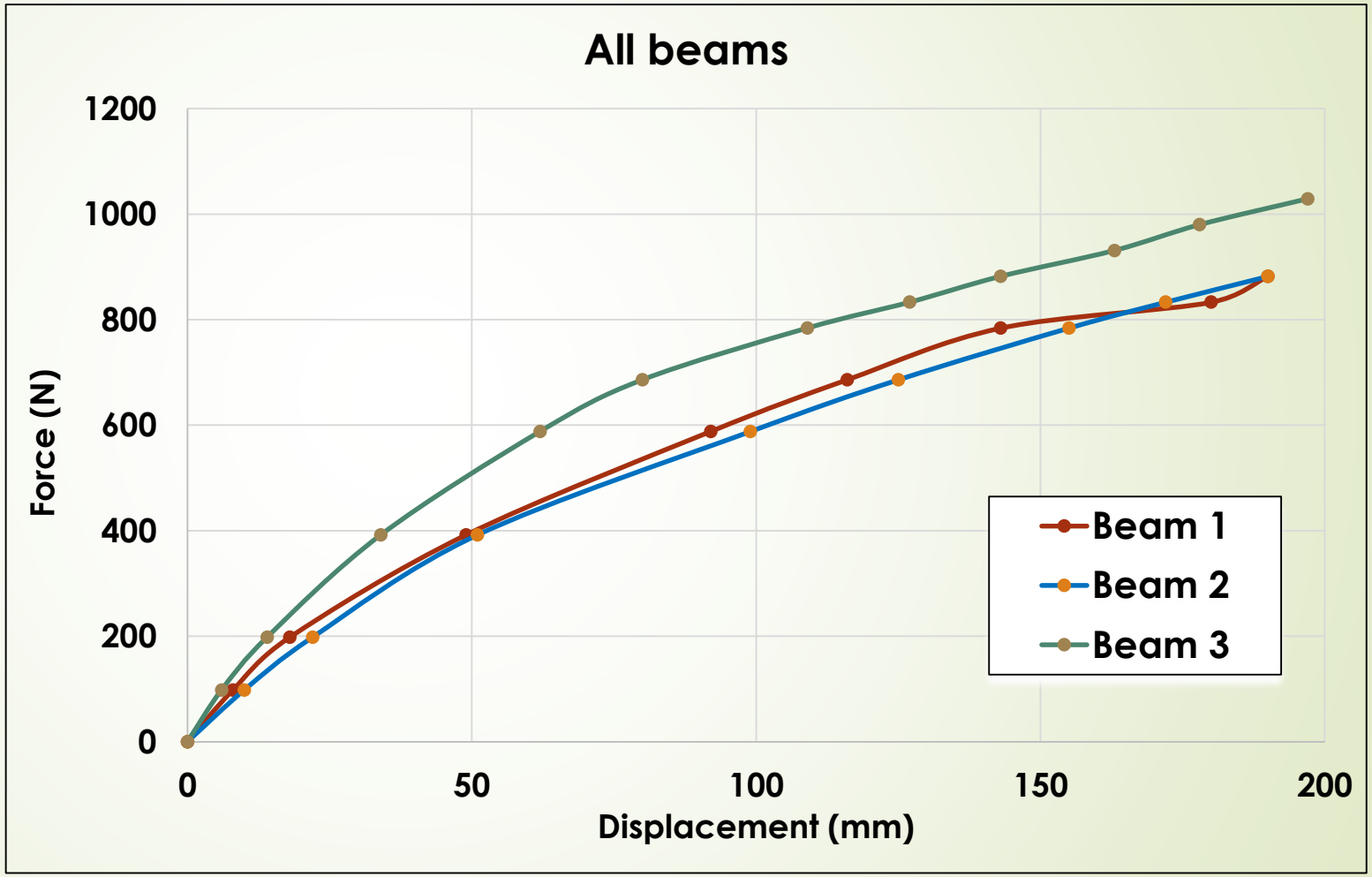
❑ Results

Beam No. 3

F_{max} = 1092 N

δ_{Max} = 19.7 cm

F_{theo} = 1619 N



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Pullout strength calculation

❖ Screw propertites

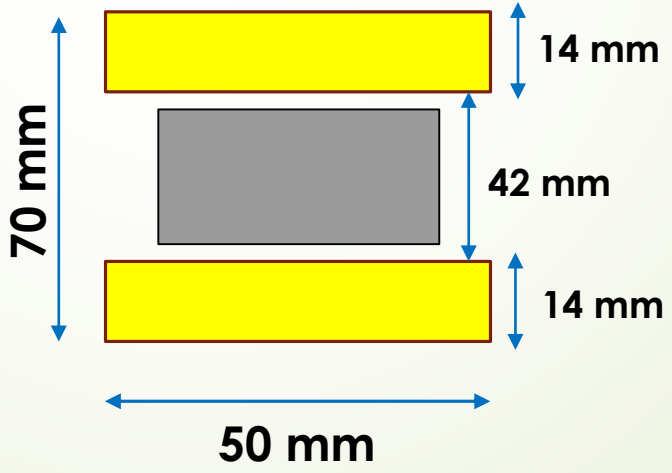
d= 3.5 mm, d_h= 8 mm L= 45 mm

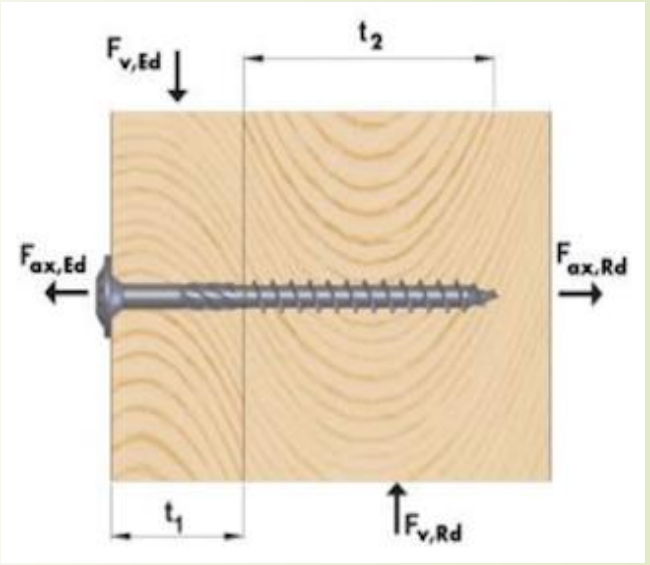
❖ Component wood 1

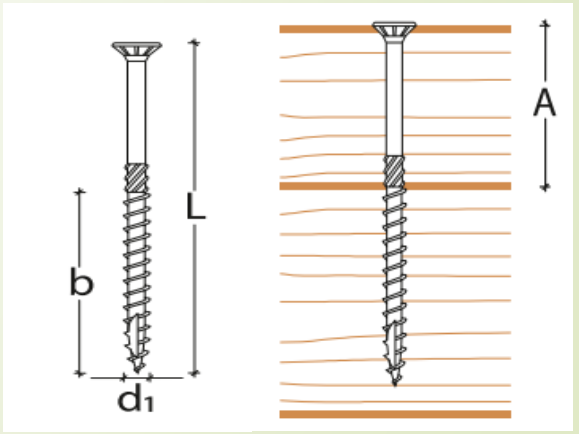
Thickness = 14 mm
$\rho_{k,1}$ = 370 kg/m³
T_1 = 14 mm

Component wood 2

Thickness = 42 mm
$\rho_{k,2}$ = 370 kg/m³
T_2 = 31 mm







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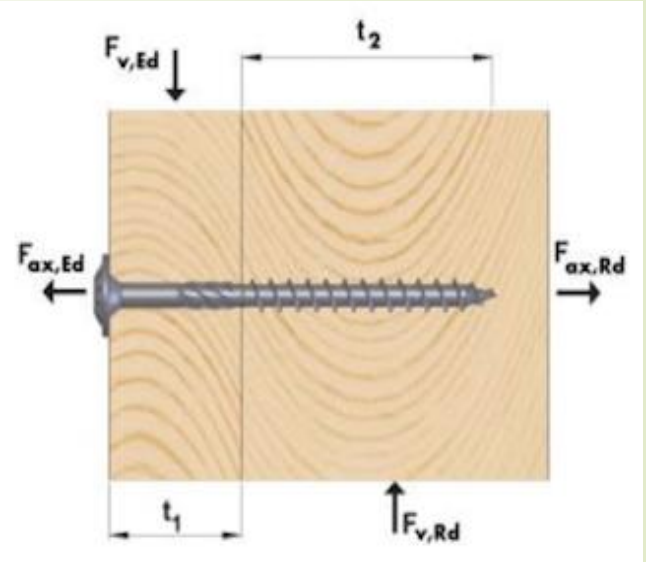
Pullout strength calculation

$F_{ax,a,Rk,1} = 811$ N

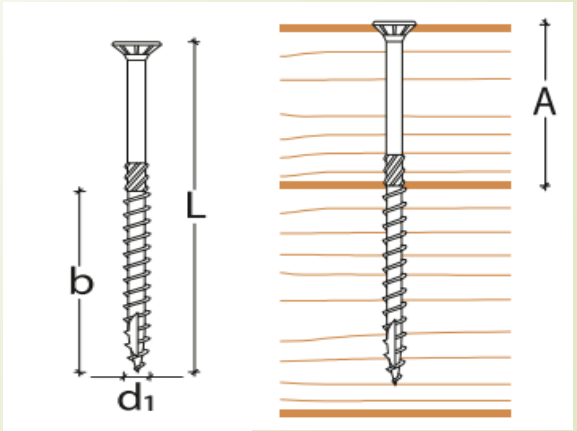
$$= k_{ax} \times f_{ax,k} \times d \times l_{ef} \times \left(\frac{\rho_k}{350}\right)^{0,8}$$

$$= F_{ax,\alpha,Rk,2} = f_{head,k} \times {d_h}^2 \times \left(\frac{\rho_k}{350}\right)^{0,8}$$

$F_{ax,a,Rk,2} =$ 683 N



$F_{ax,a,Rk} =$ 683 N



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Shear resistance Fv,RK

a) 1872 N

b) 1479 N

c) 705 N

a) 746 N

b) <u>635 N</u>

c) 666 N

$$= f_{h,1,k} \times t_1 \times d$$

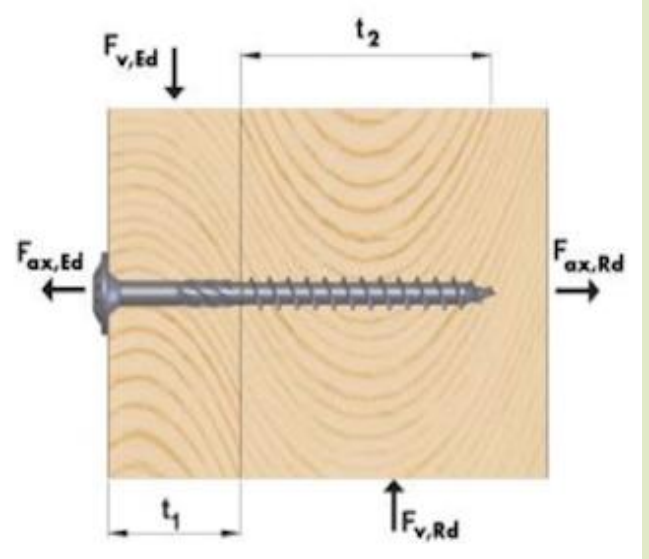
$$= f_{h,2,k} \times t_2 \times d$$

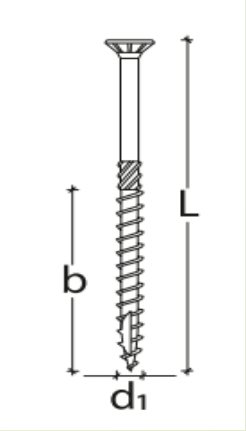
$$= \frac{f_{h,1,k} \times t_1 \times d}{1+\beta}\left[\sqrt{\beta + 2\beta^2\left[1+\frac{t_2}{t_1}+\left(\frac{t_2}{t_1}\right)^2\right]+\beta^3\left(\frac{t_2}{t_1}\right)^2}-\beta\left(1+\frac{t_2}{t_1}\right)\right]+\frac{F_{ax,Rk}}{4}$$

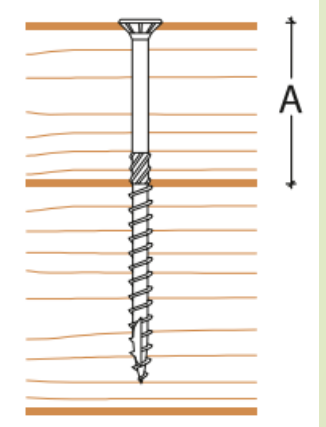
$$= 1{,}05\frac{f_{h,1,k} \times t_1 \times d}{2+\beta}\left[\sqrt{2\beta(1+\beta)+\frac{4\beta(2+\beta) \times M_{y,Rk}}{f_{h,1,k} \times d \times {t_1}^2}}-\beta\right]+\frac{F_{ax,Rk}}{4}$$

$$= 1{,}05\frac{f_{h,1,k} \times t_2 \times d}{1+2\beta}\left[\sqrt{2\beta^2 \times (1+\beta)+\frac{4\beta(1+2\beta) \times M_{y,Rk}}{f_{h,2,k} \times d \times {t_2}^2}}-\beta\right]+\frac{F_{ax,Rk}}{4}$$

$$= 1{,}15\sqrt{\frac{2\beta}{1+\beta}}\sqrt{2M_{y,Rk} \times f_{h,1,k} \times d}+\frac{F_{ax,Rk}}{4}$$







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Strain gages

- Strain gages between 3-5 %.
- For the steel parts, the gages should installed before beam fabrication.
- Installation at the top and bottom surface are possible.
- Gauges between wood and steel is possible.

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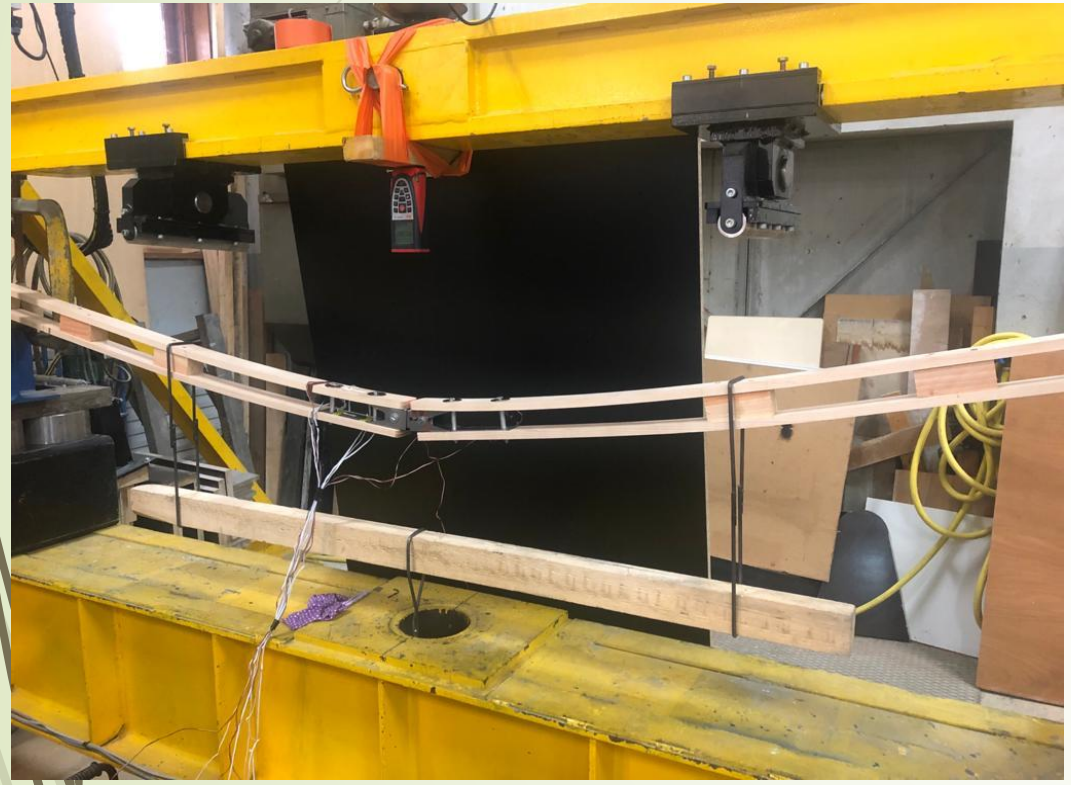
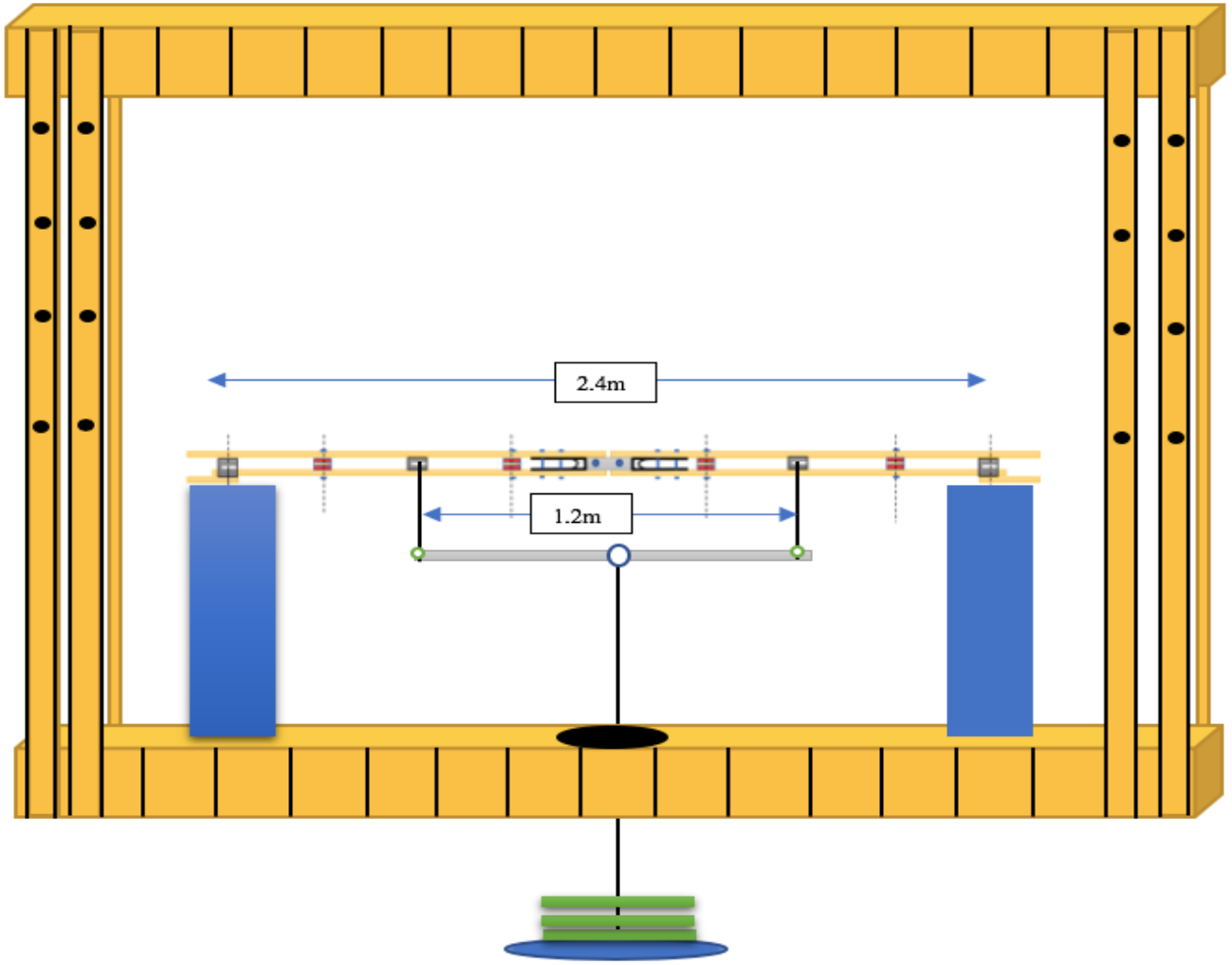
Test Protocol





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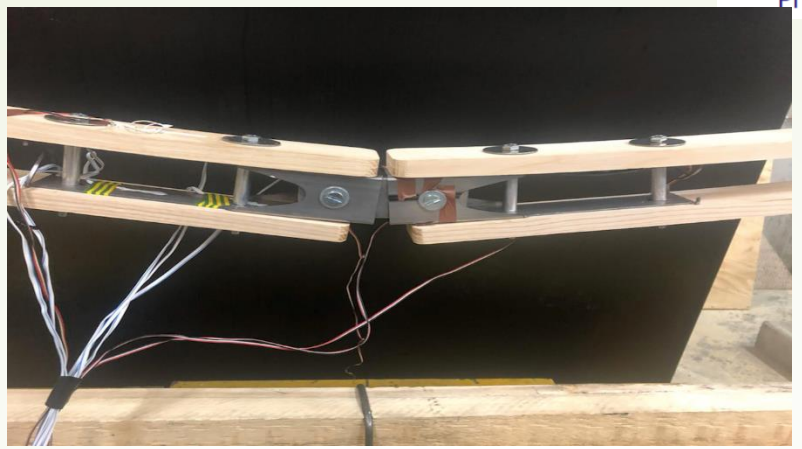
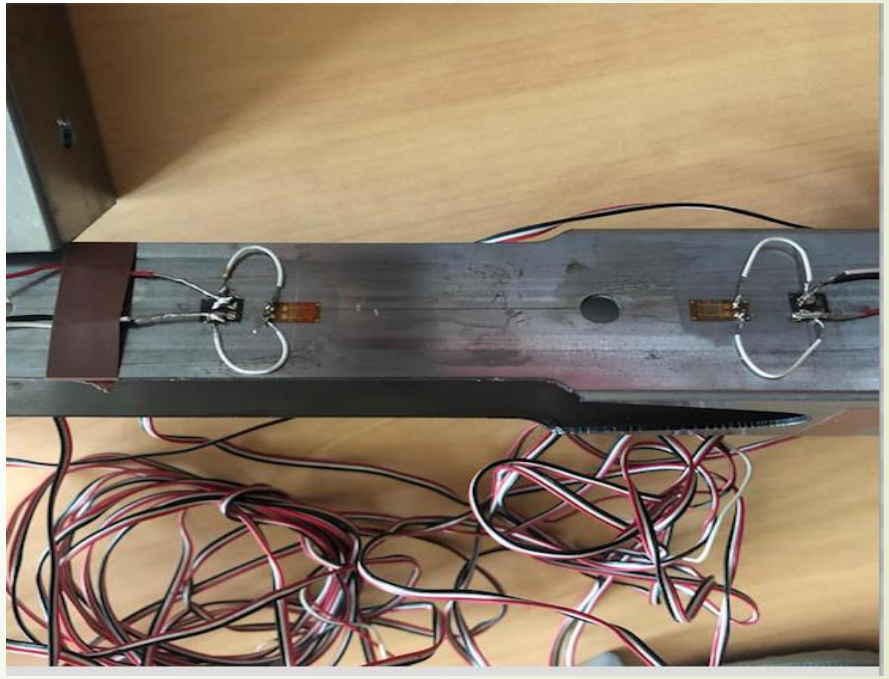
Strain gauges



Strain gauges on internal side



Strain gauges on internal side

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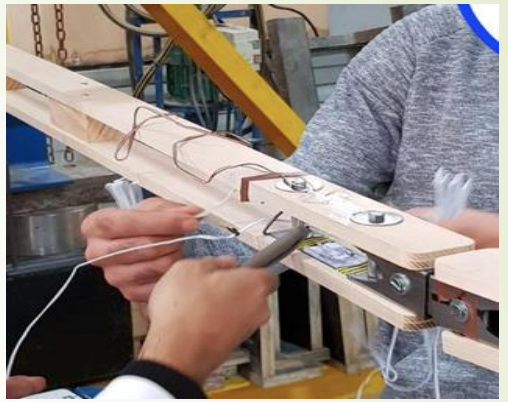
2 screws



The beam was not completely horizontal because of space between steel pieces

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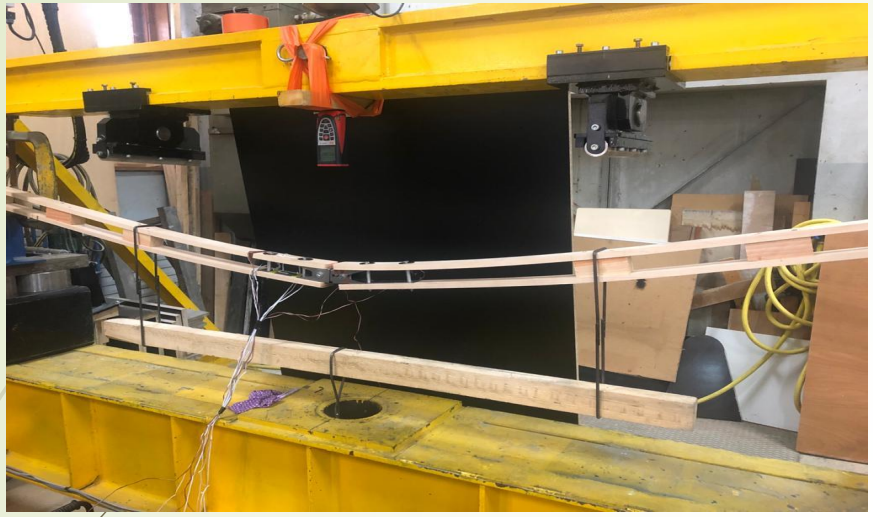

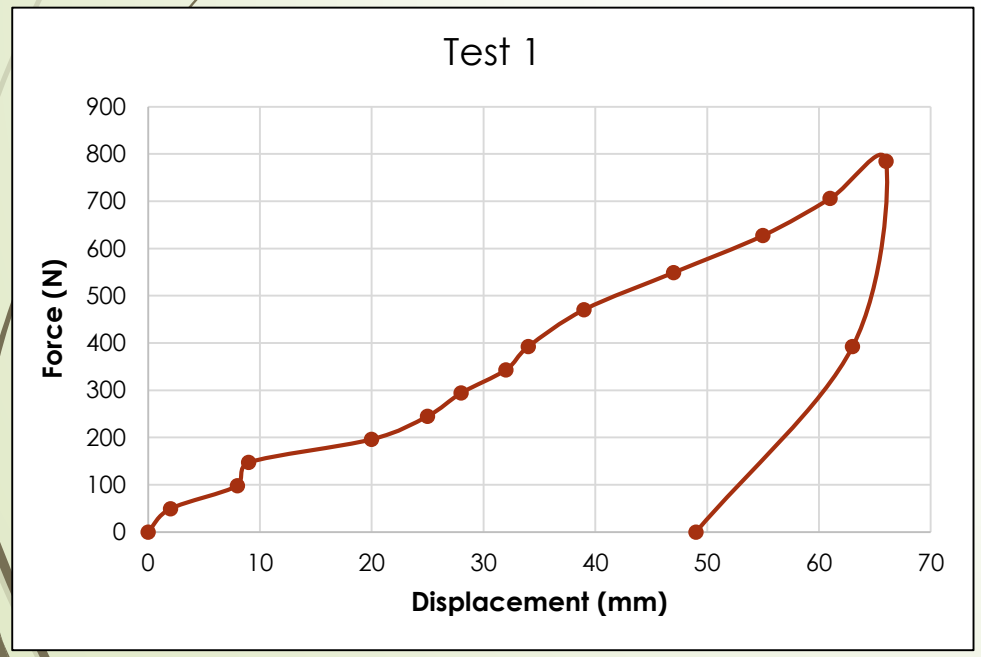

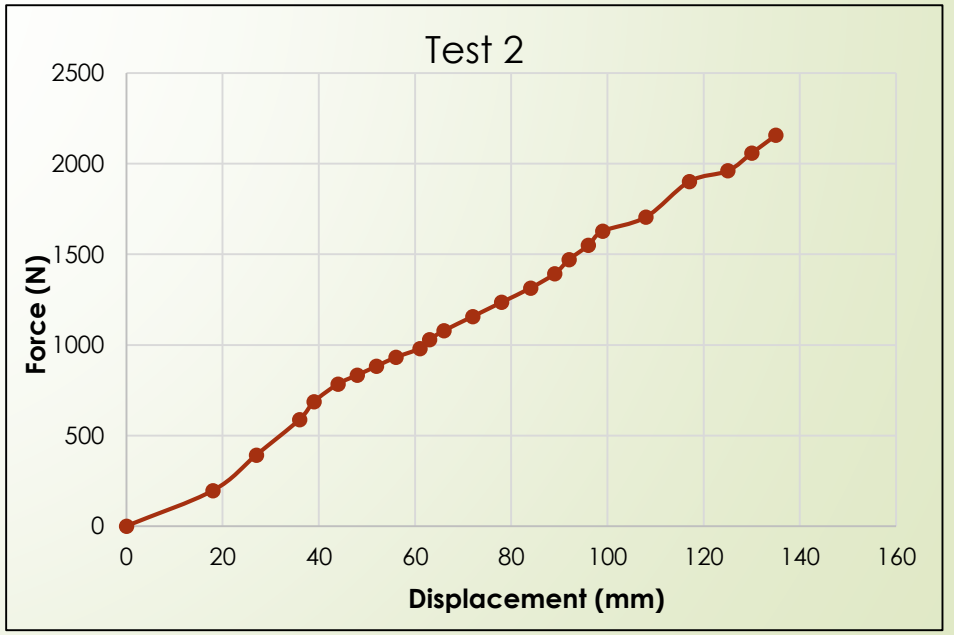

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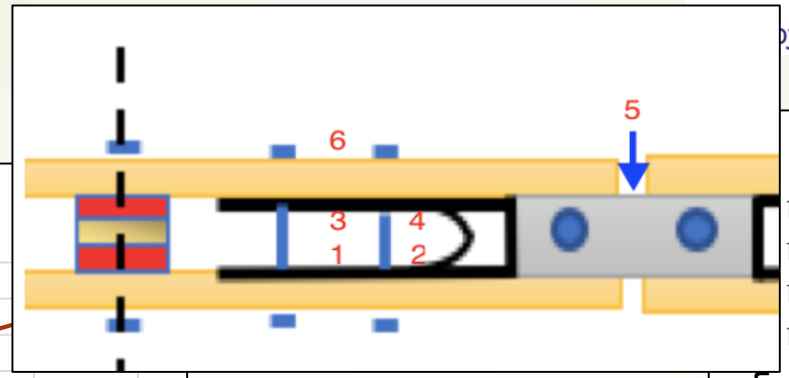

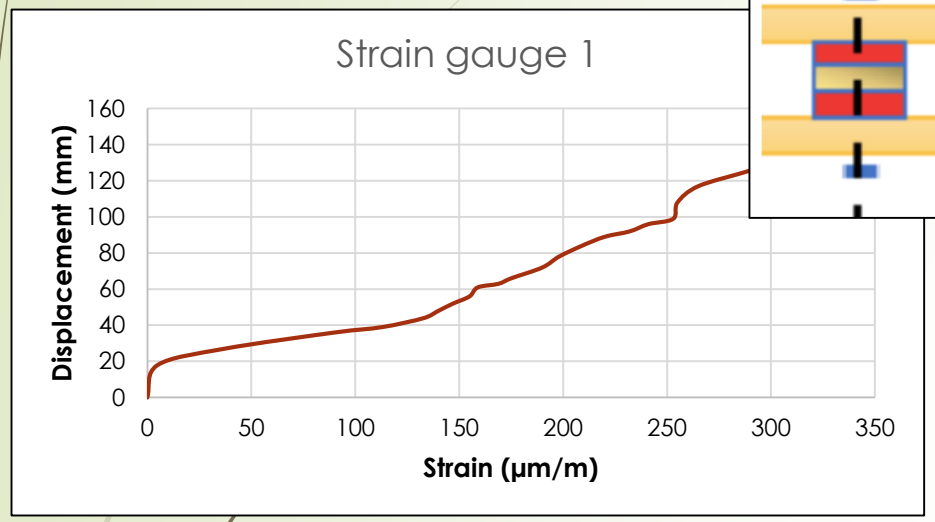

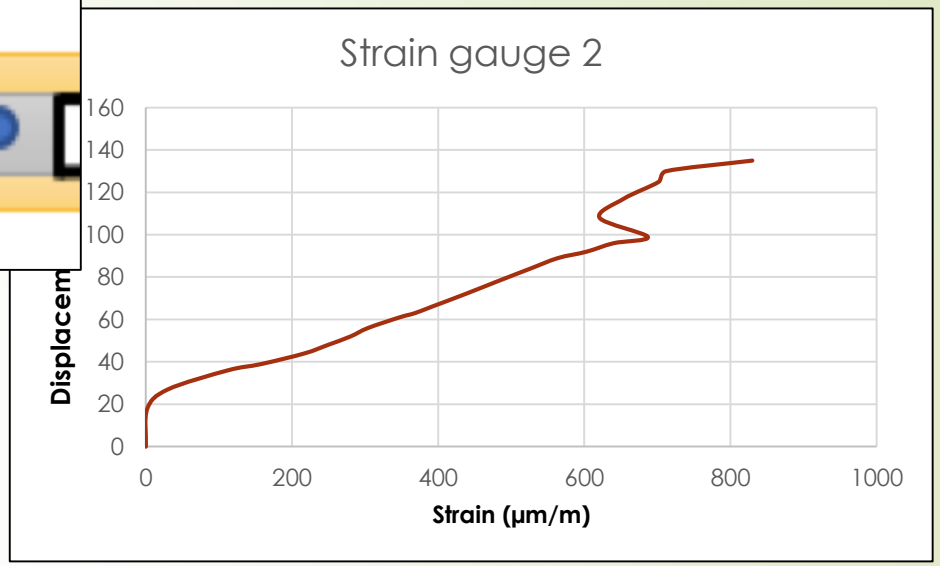

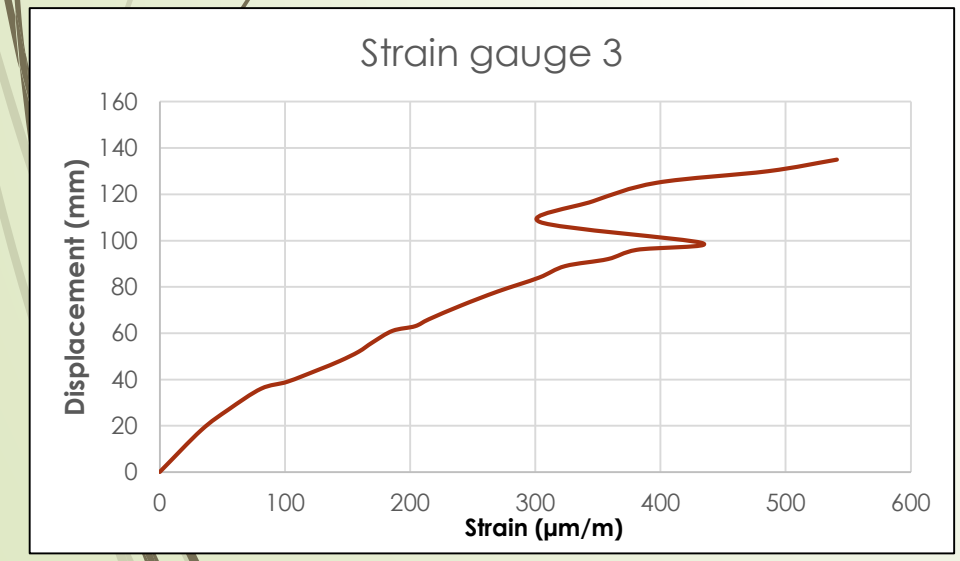

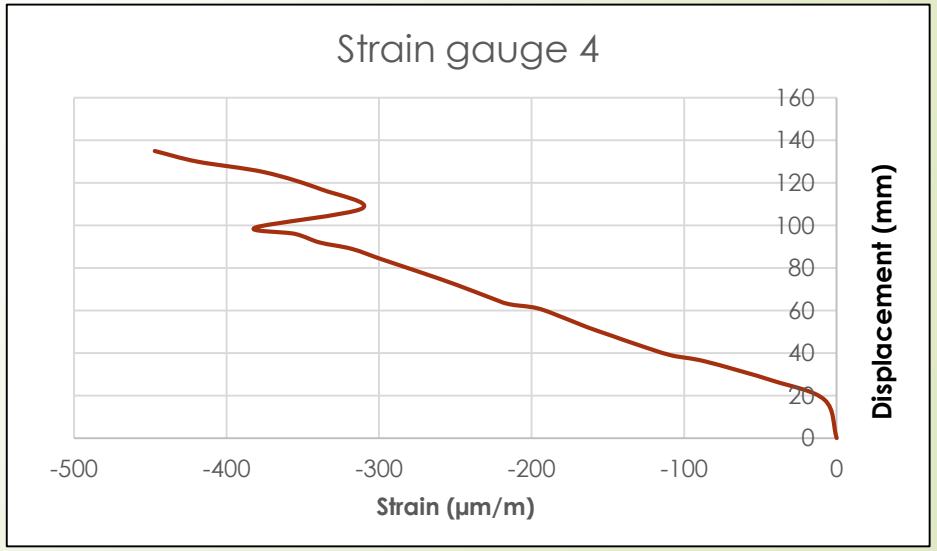

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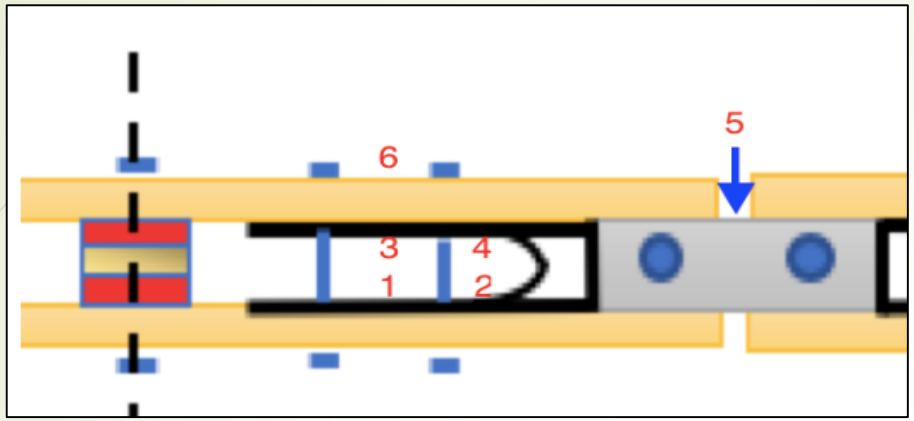

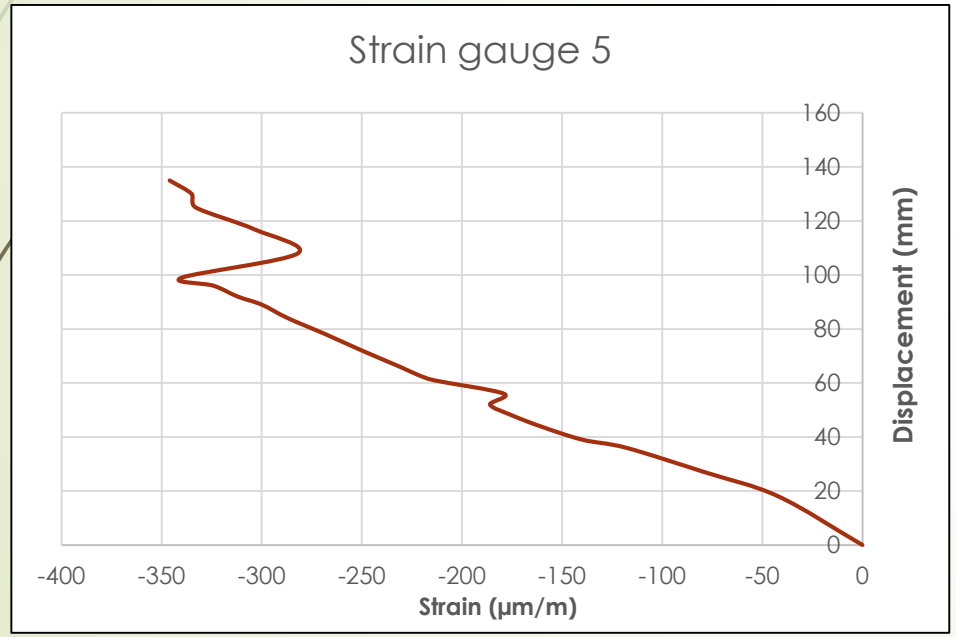

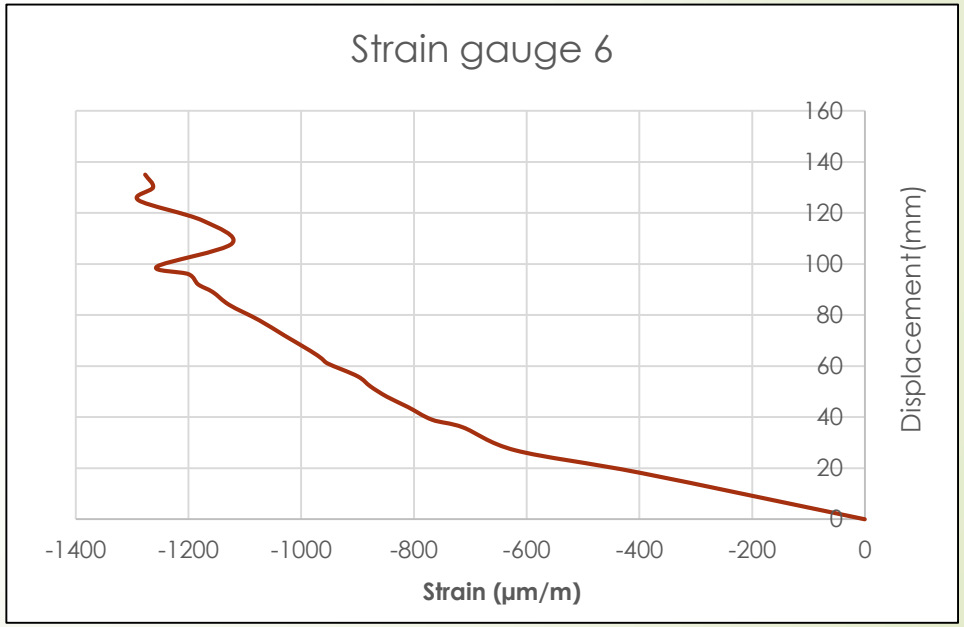

External gauges were damaged during the test

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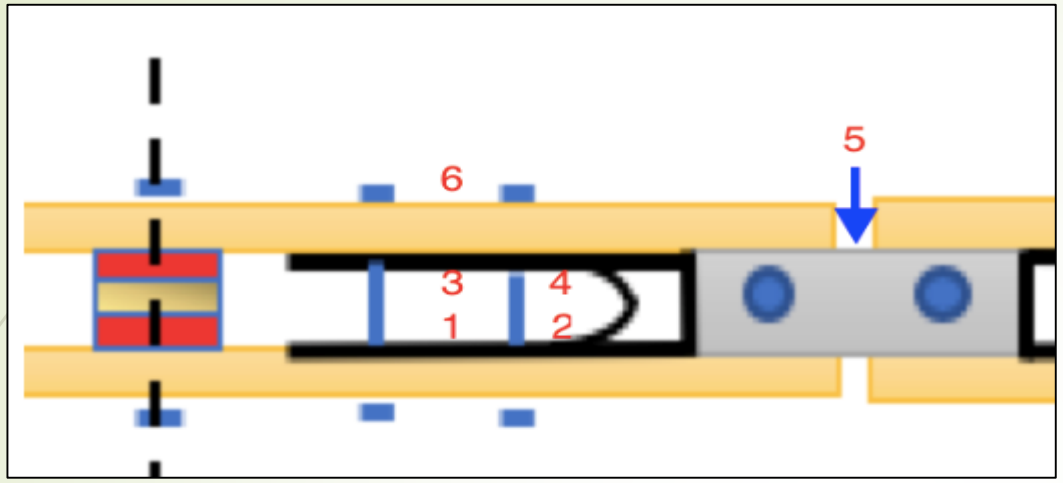

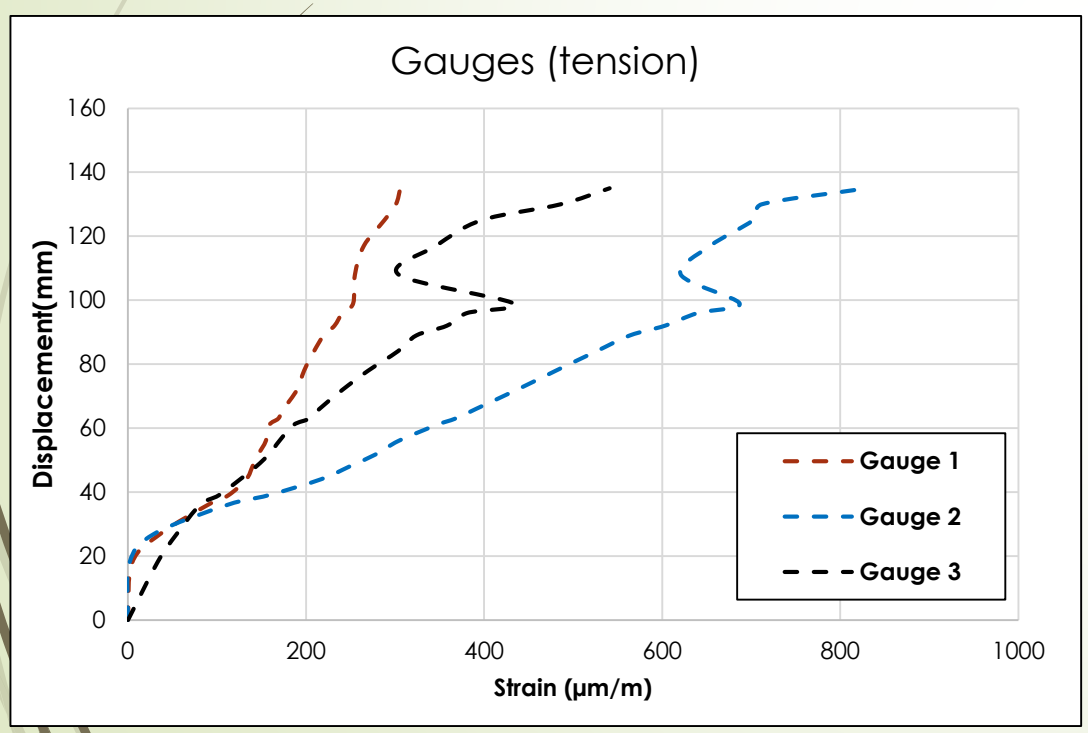

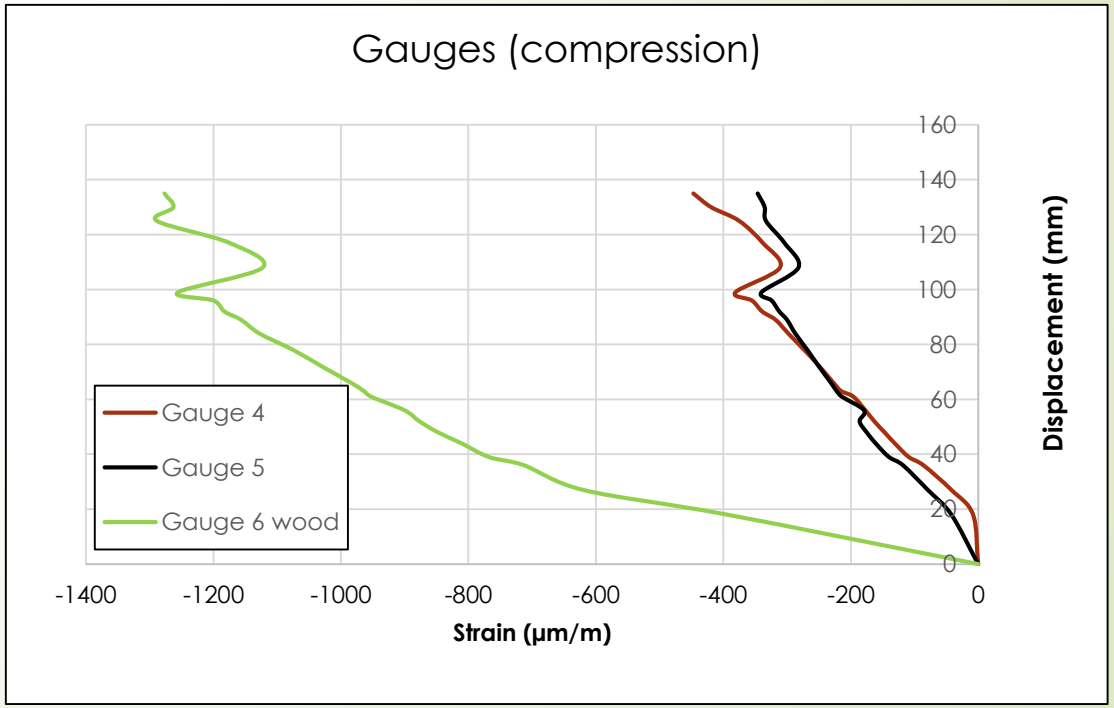

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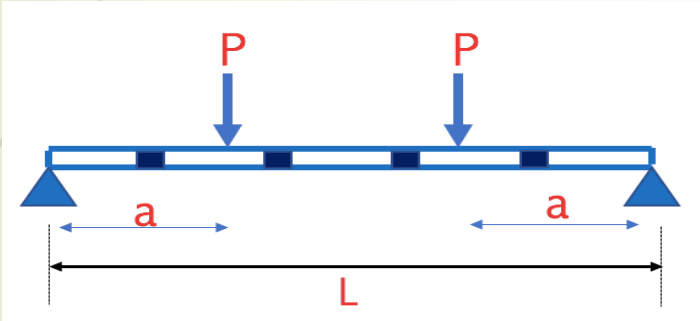
Wooden beam of gridshell without assembly

Theoretical model



$$M = P.\,a$$

$$\Delta_{max}\ (\text{middle}) = \frac{P.a}{24\,EI}\,(3L^2 - 4\,a^2)$$

$$I = 2 \times \frac{b t^3}{12} + 2 \times b \times t\left(\frac{h}{2} - \frac{t}{2}\right)^2$$

Experimental test

Deflection Δ_{max} measurable

Rotation θ measurable

Inertia I measurable

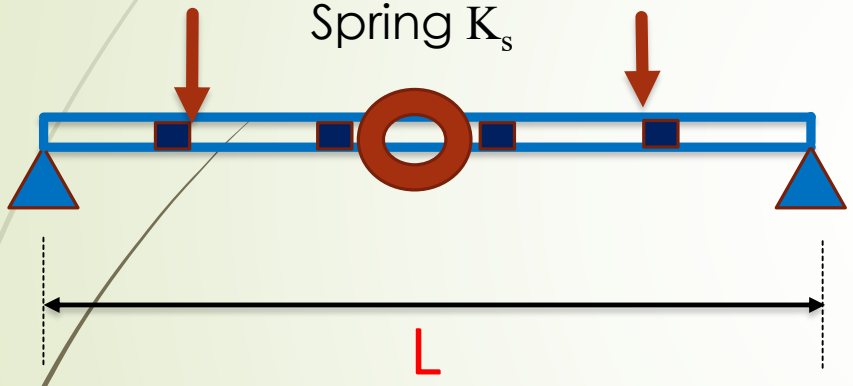
Δ_{theo} **depends on I** $\rightarrow$ $I_{real} = K_I\, I_{theo}$ $\leftrightarrow$ $I_{theo} \neq I_{real} = \dfrac{P.a}{24\,E\,\Delta exp}\,(3L^2 - 4\,a^2)$

$$\Delta_{theo} = k_d\, \Delta_{exp}$$

Projet cofinancé par le Fonds Européen de Développement Régional

Wooden beam of gridshell with assembly

Theoretical model



$$\Delta(x) = \int \theta(x)\,dx = \iint \frac{M(x)}{E(x)I(x)}\,dx^2$$

Δ_{max} for the beam with assembly = f (I_{exp} , Ks)

Experimental test

Deflection Δ_{max} measurable

Rotation θ measurable

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Expected output results

- moment of inertia factor (K_I) ; taking into account the shear effects.
- Force – stiffness diagram.
- Force – rotation diagram experimentally (beam without assembly)
- Force - rotation diagram experimentally (beam with assembly)
- Moment – rotation diagram (for assembly)

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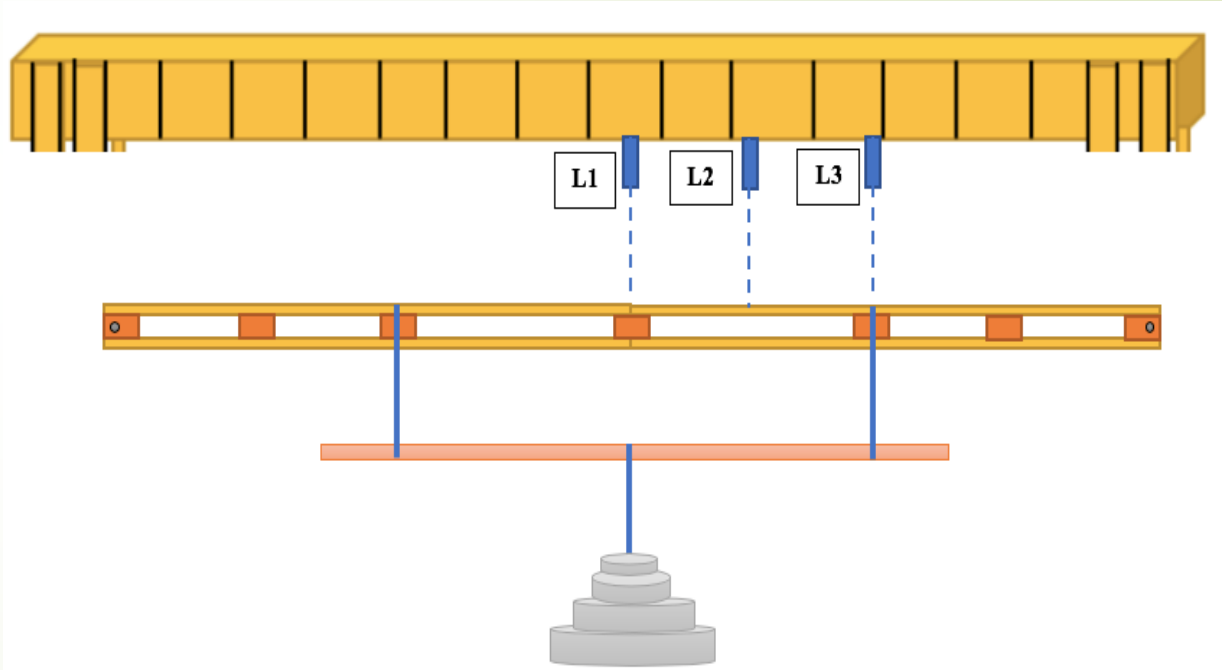
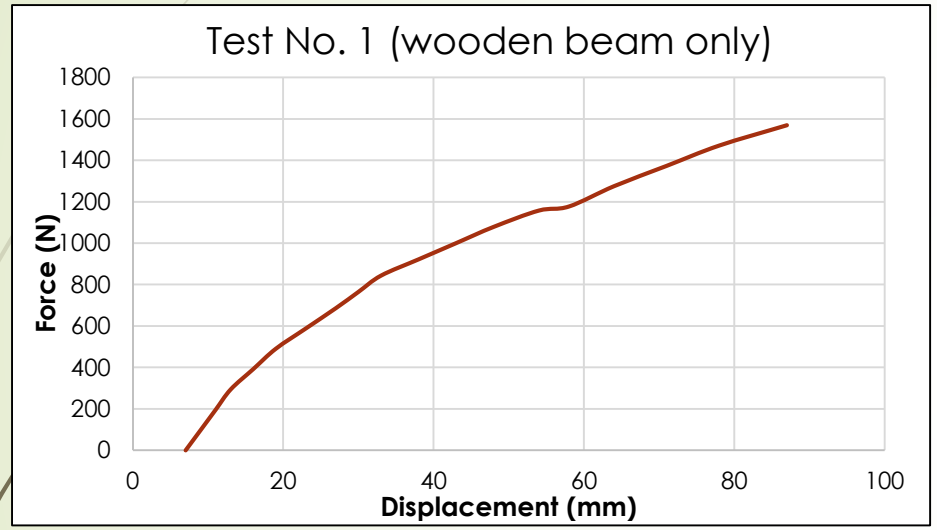
Flexural 4 points main test (wooden beams)

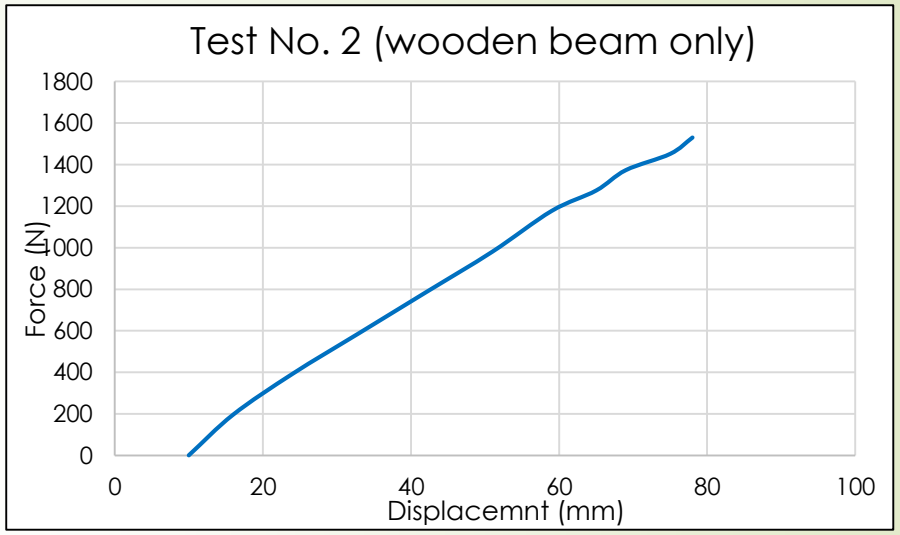


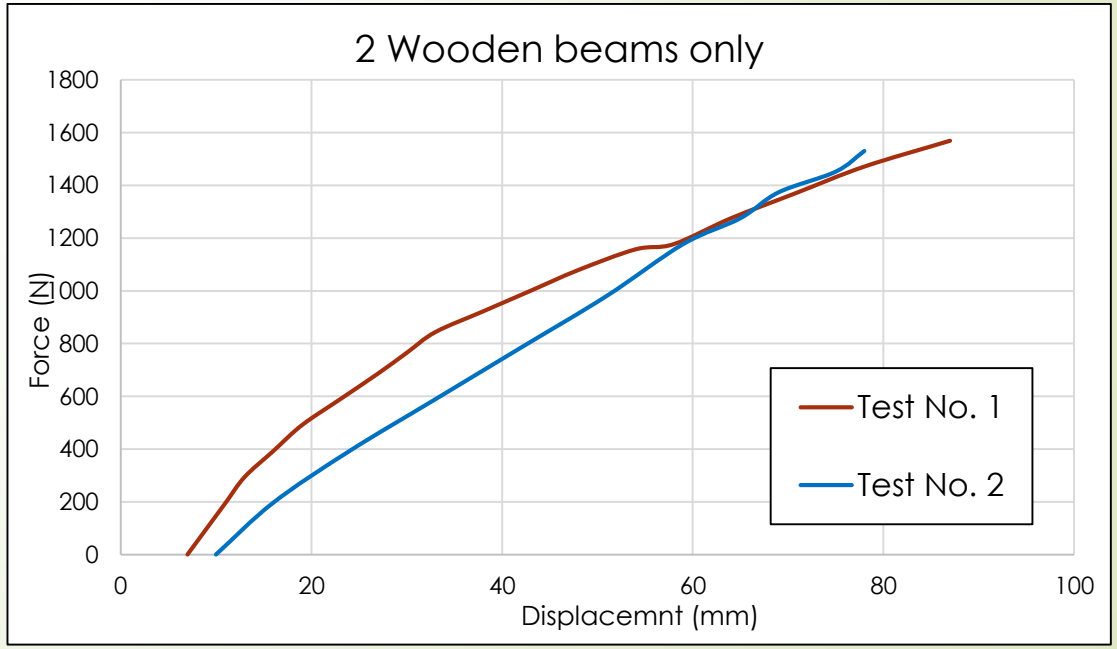
- **2 wooden beams only (without assembly)**
- **3 laser devices (L1, L2, L3 to measure the displacement)**

Flexural test of wooden beams only



- Elastic behaviour
- Initial displacement of test 1 = 7mm
- Initial displacement of test 2 = 10 mm





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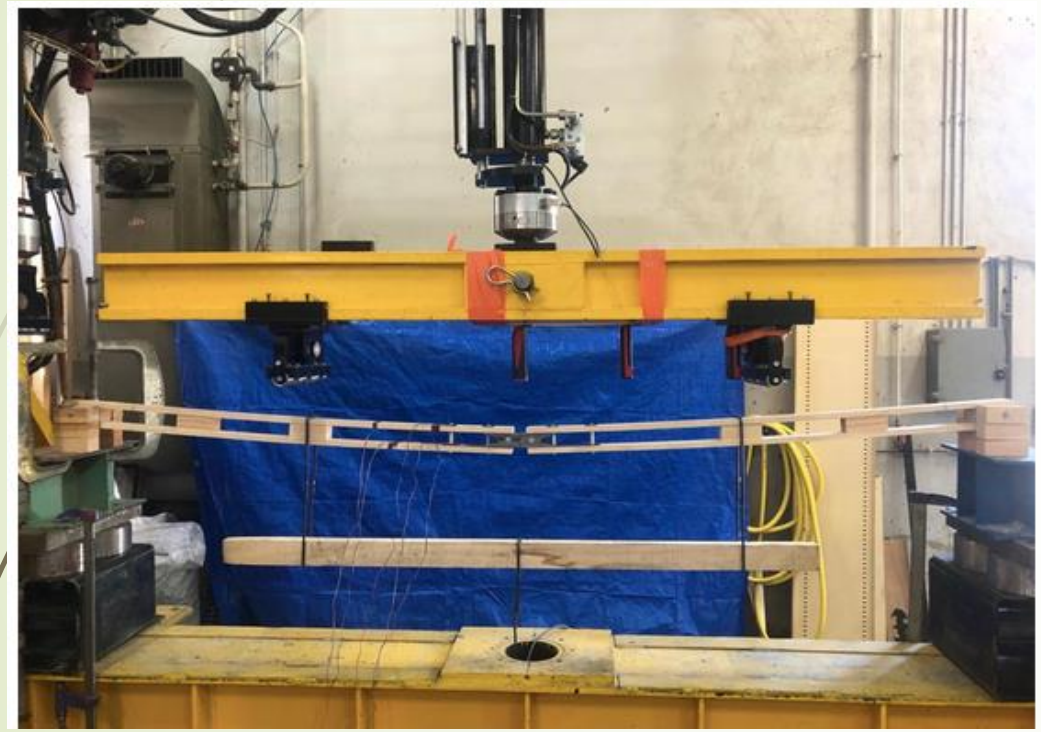
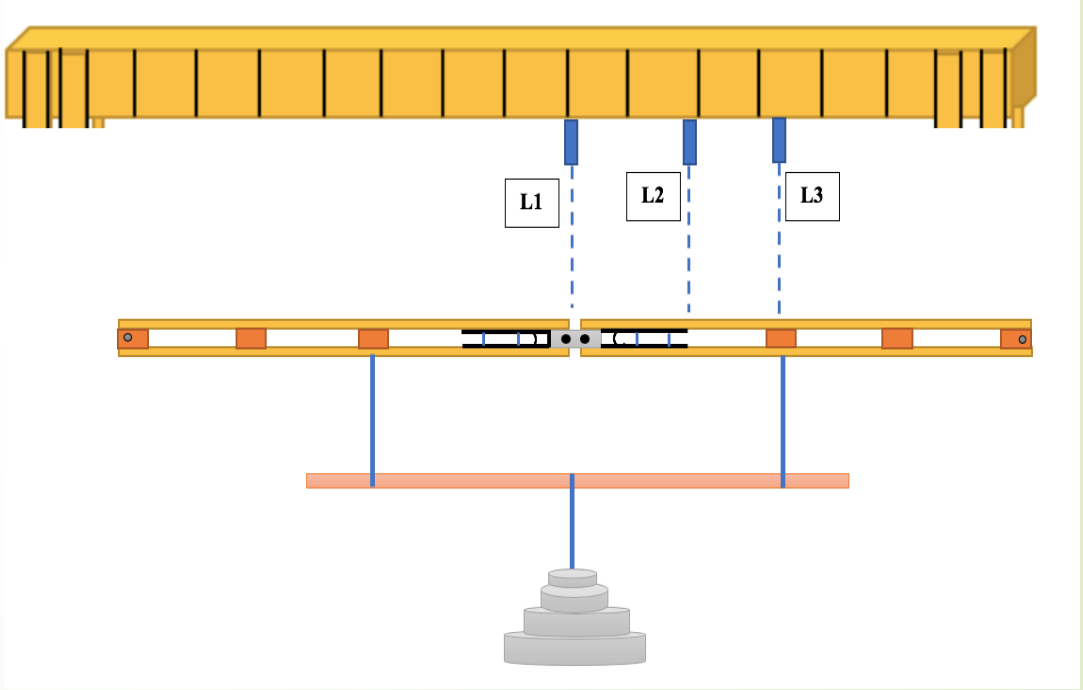
Flexural 4 points main test (with assembly)





- **2 wooden beams with metallic assembly.**
- **3 laser devices (L1, L2, L3 to measure the displacement).**

Flexural test of wooden beams with assembly

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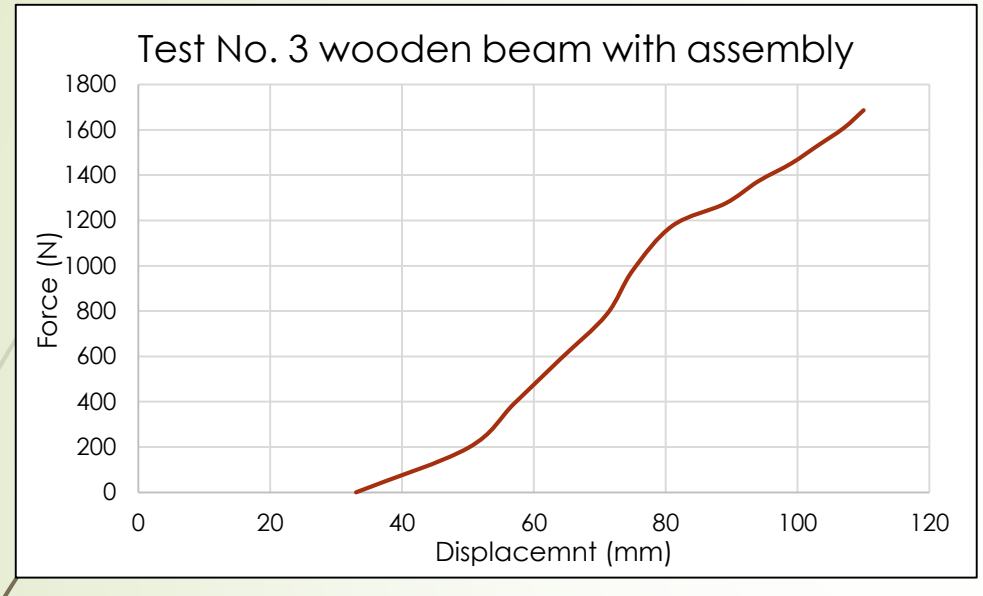
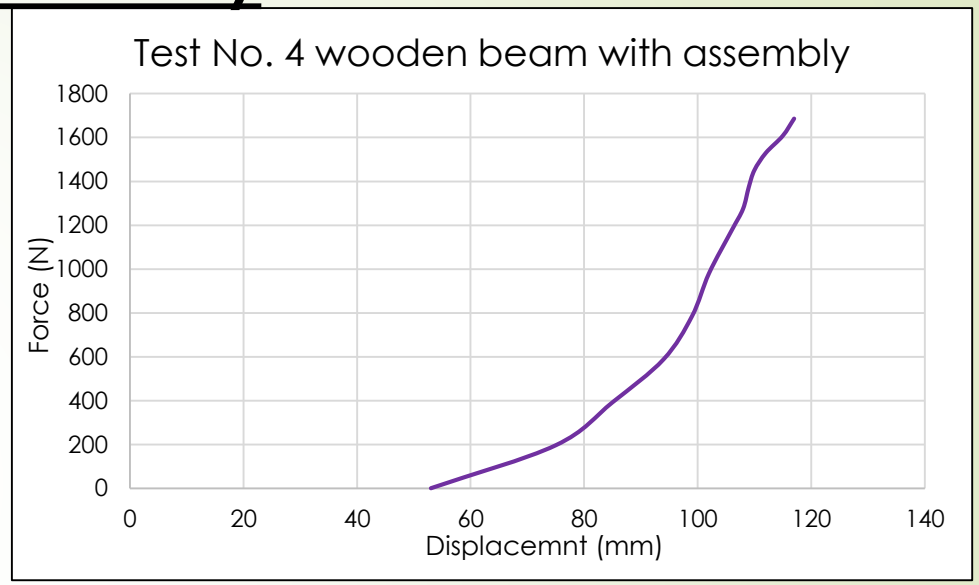
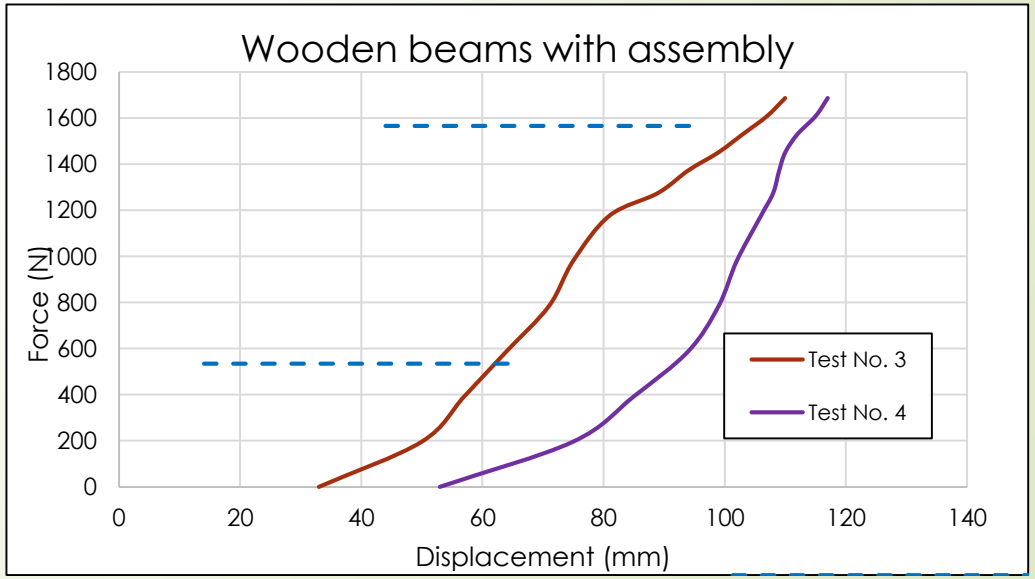




- Elastic behaviour
- Initial displacement of test 3 = 33 mm
- Initial displacement of test 4 = 53 mm
- Rigidity of beam after 200 N.



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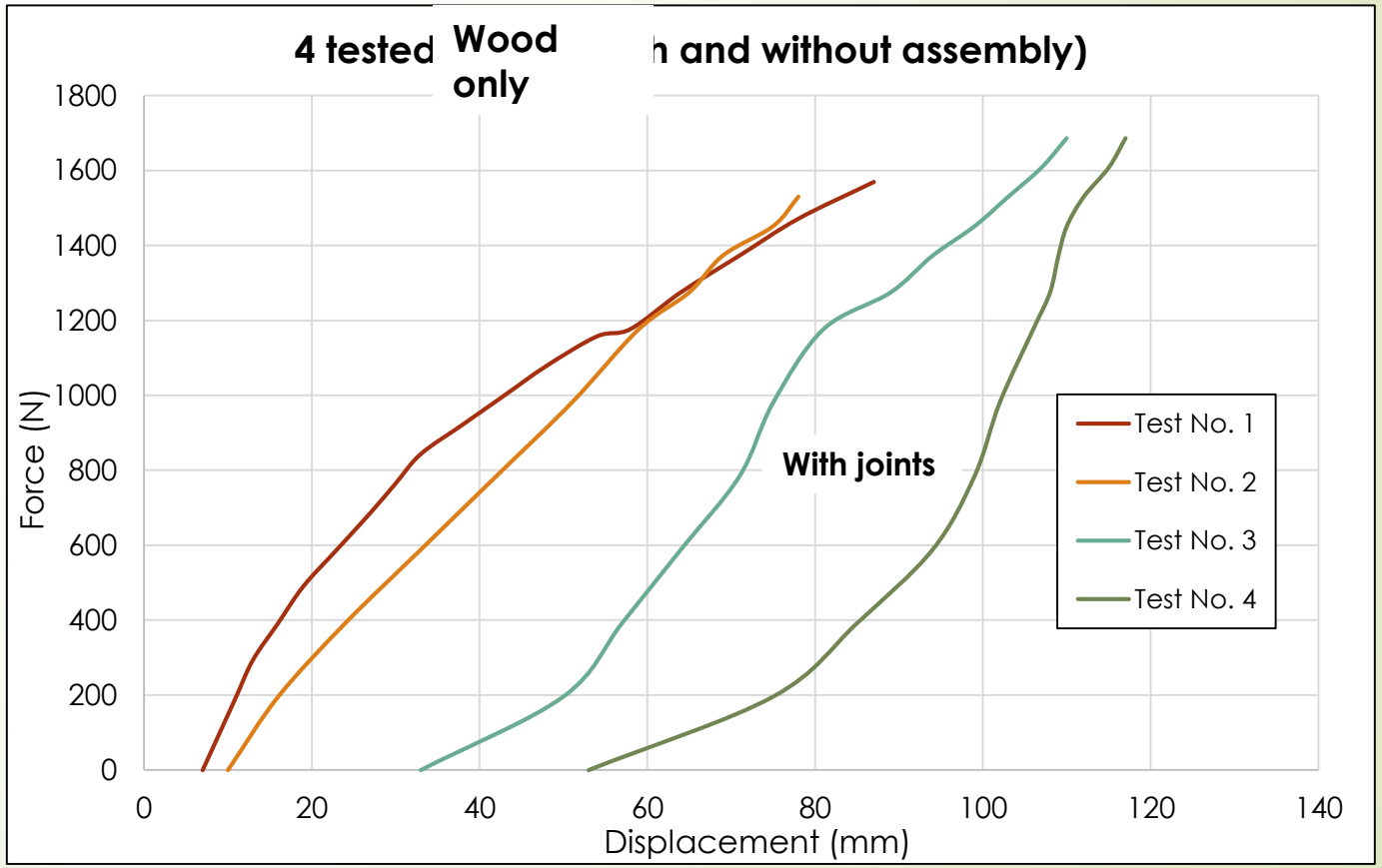
Comparison between beam (with and without assembly

Wooden beams

- Initial displacement difference = 3 mm

Wooden beams with assembly

- Initial displacement difference = 20 mm



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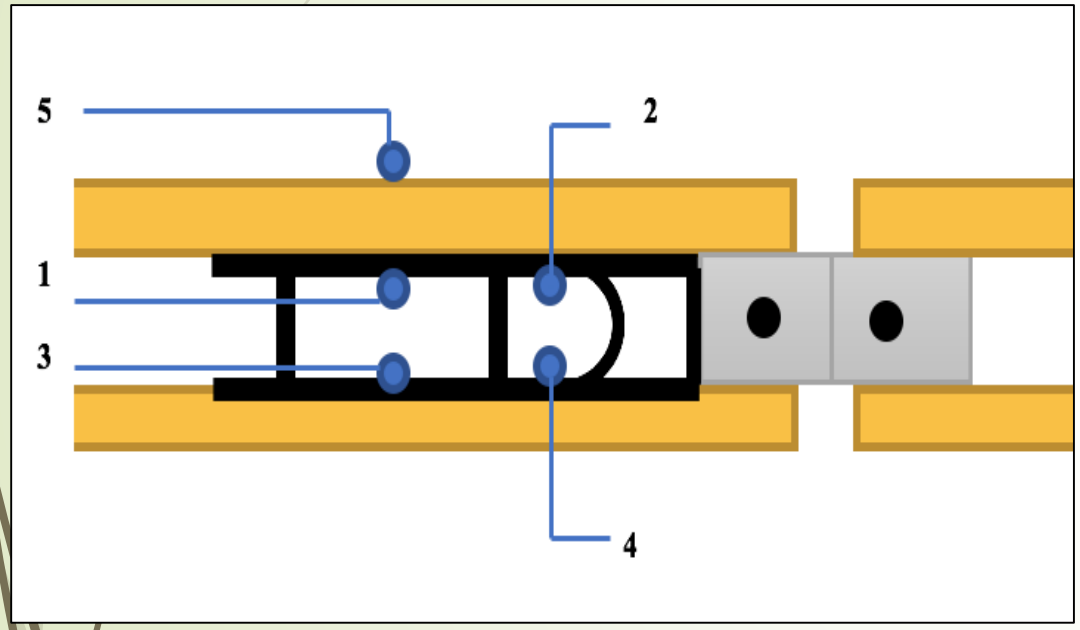
Strain gauges on the assembly and wood

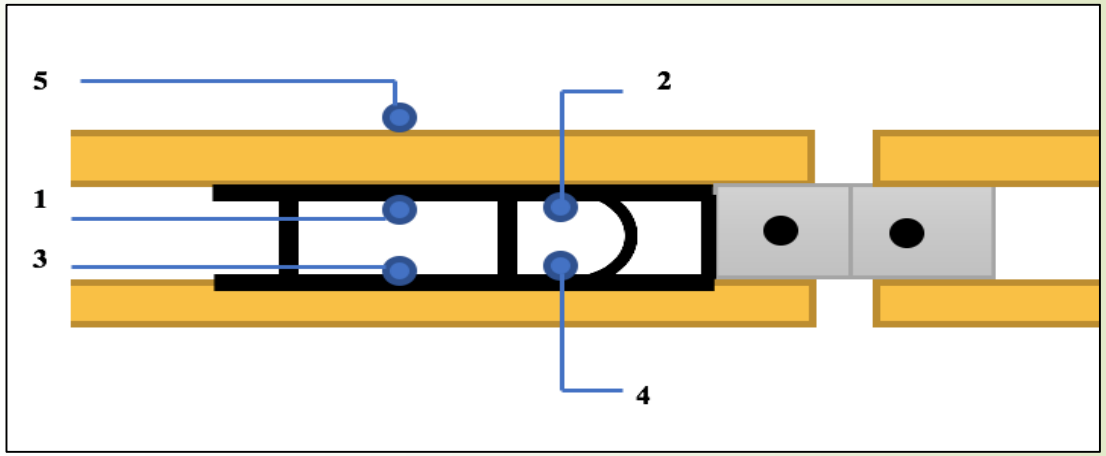


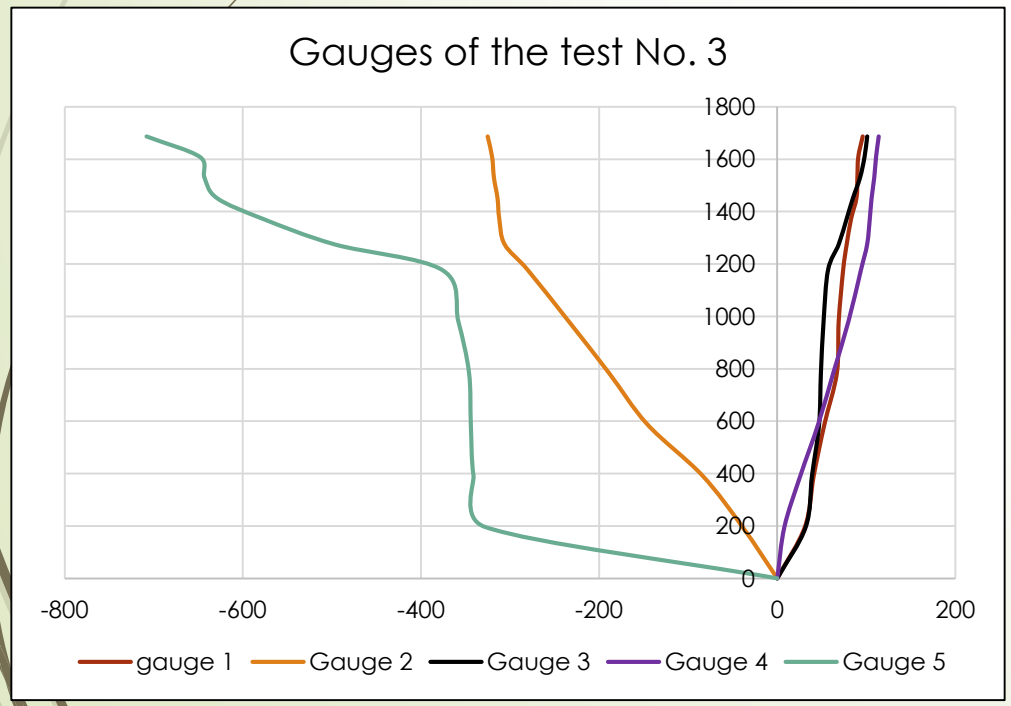
Ideal case

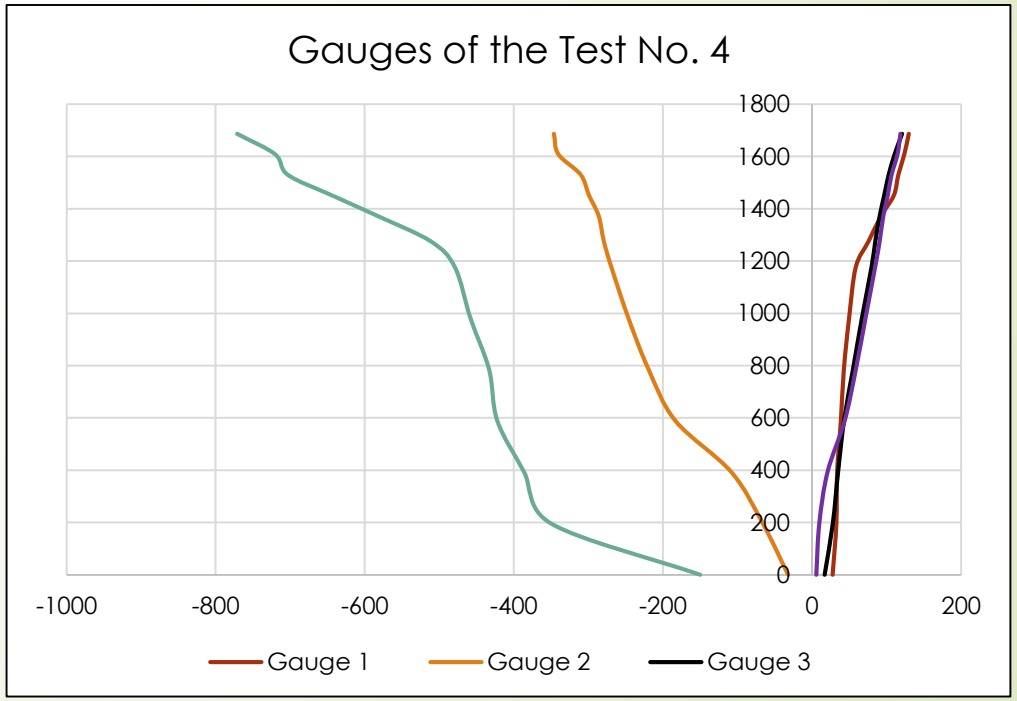
Gauge 1,2 and 5 under compression (-)
Gauge 3 and 4 under tension (+)

Strain gauges results

- Gauge No. 1 under tension (+)
- Top surface of assembly is not working perfectly with the top layer of wood







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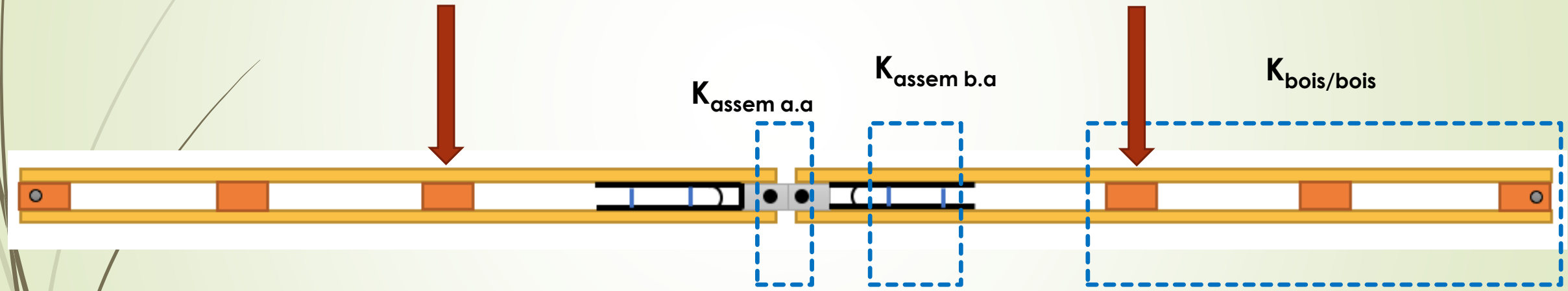
Rigidity and moment of Inertia (Eurocode)



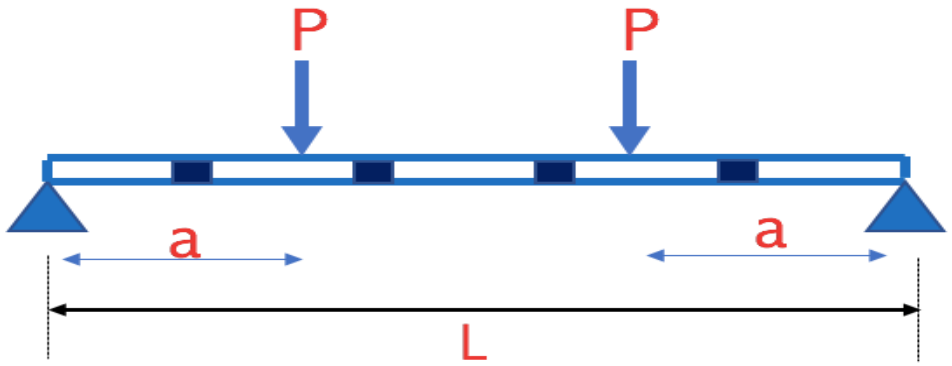
Experimental Inertia

$$\delta_{max} \text{ at (center)} = \frac{P.a}{24\,EI}(3L^2 - 4\,a^2)$$

$$I_{exp} = \frac{P.a}{24\,E\,\delta exp}(3L^2 - 4\,a^2)$$

$$I_{eq} = 2\,I_1 + \frac{A_1\ \gamma_1\ a^2}{1 + \gamma_1}$$

$$K_i = I_{exp} / \ I_{eq}$$



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Experimental inertia for beam No. 3

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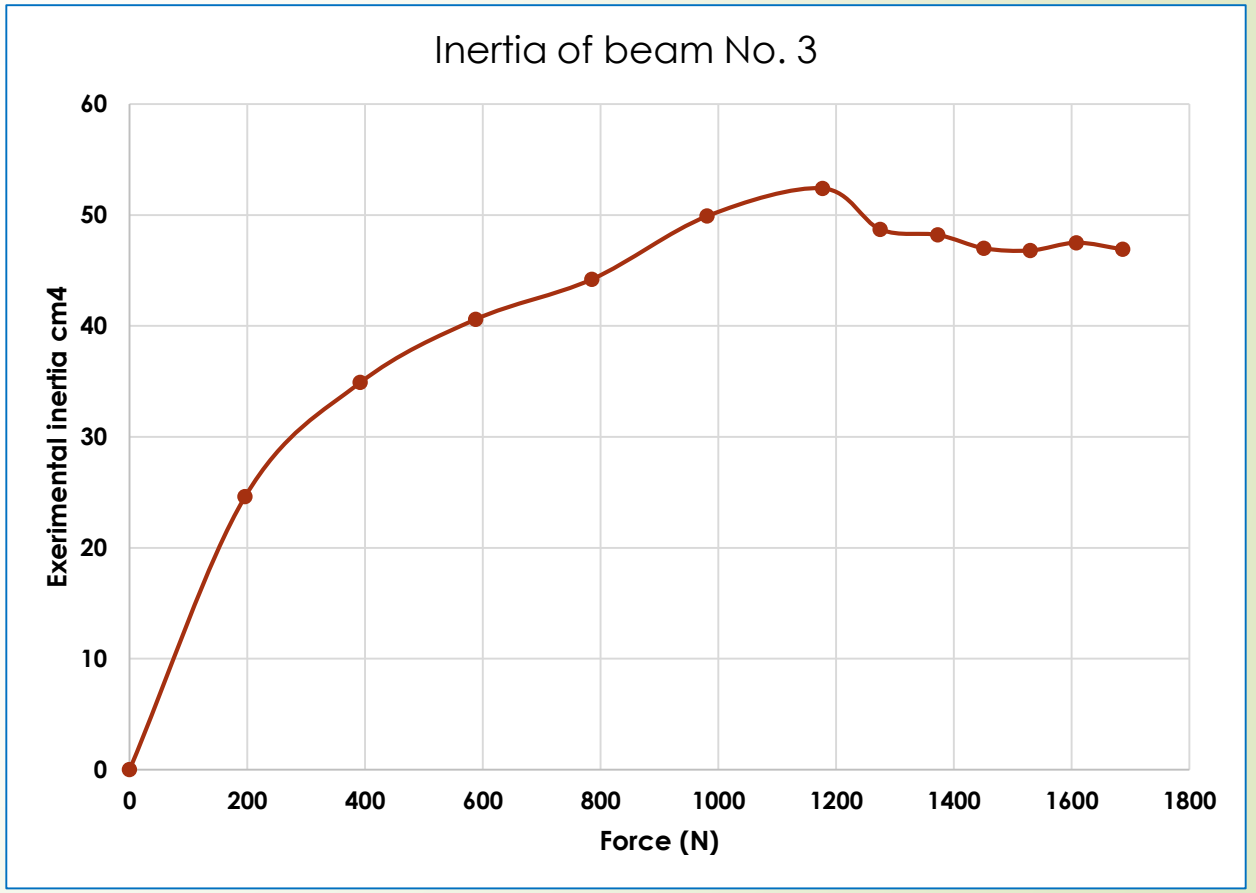
Force F (N)	load P	dis mm	dis net	I exp cm4	ki = Iexp/Ieq
0	0	33	0	0	**0.00**
196	98	50	17	24.6	**0.51**
392	196	57	24	34.9	**0.72**
588	294	64	31	40.6	**0.84**
785	392.5	71	38	44.2	**0.92**
981	490.5	75	42	49.9	**1.03**
1177	588.5	81	48	52.4	**1.08**
1275	637.5	89	56	48.7	**1.01**
1373	686.5	94	61	48.2	**1.00**
1451	725.5	99	66	47	**0.97**
1530	765	103	70	46.8	**0.97**
1608	804	107	74	47.5	**0.98**
1687	843.5	110	77	46.9	**0.97**



$$I_{eq} = 48.39 \text{ cm}^4$$

Experimental inertia for beam No. 4

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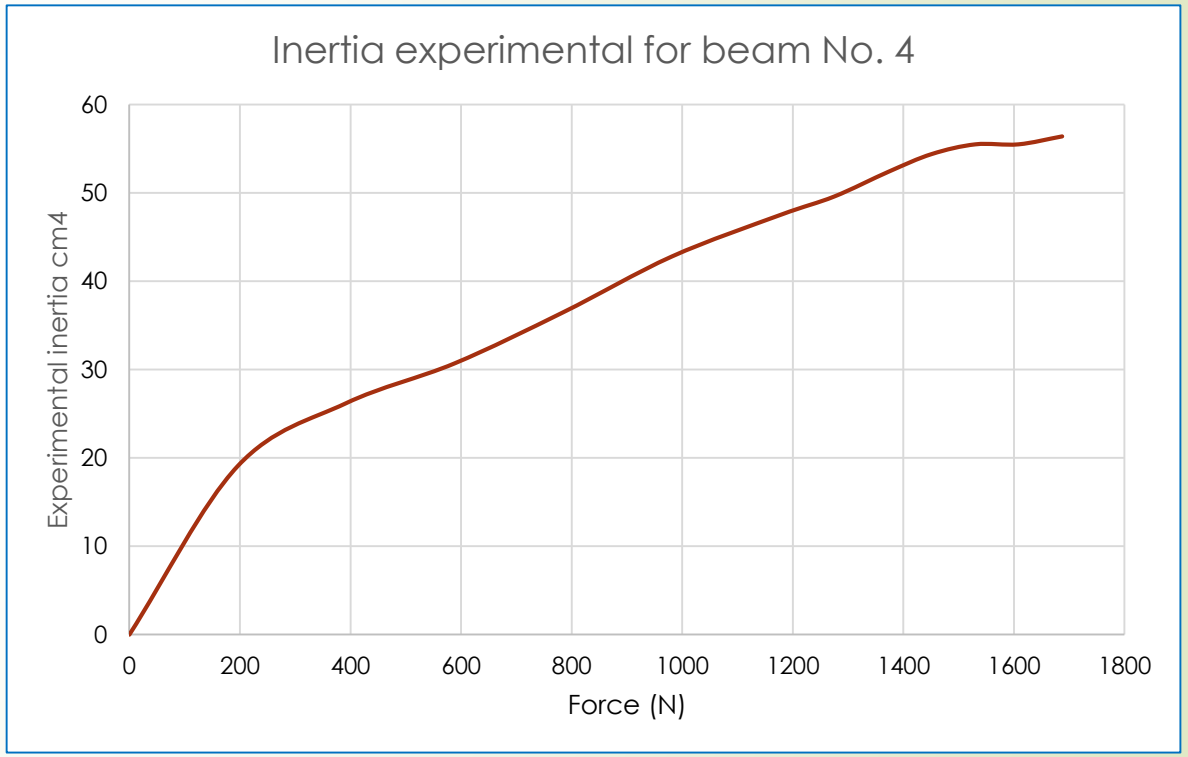
Force F (N)	load P	Dip mm	Dip net	I exp cm4	ki = I exp/I eq
0	0	53	0	0	**0.00**
196	98	75	22	19.08	**0.40**
392	196	85	32	26.2	**0.54**
588	294	94	41	30.7	**0.64**
785	392.5	99	46	36.5	**0.76**
981	490.5	102	49	42.8	**0.89**
1177	588.5	106	53	47.5	**0.98**
1275	637.5	108	55	49.6	**1.03**
1373	686.5	109	56	52.4	**1.08**
1451	725.5	110	57	54.4	**1.13**
1530	765	112	59	55.5	**1.15**
1608	804	115	62	55.5	**1.15**
1687	843.5	117	64	56.4	**1.17**



$$I_{eq} = 48.39 \text{ cm}^4$$

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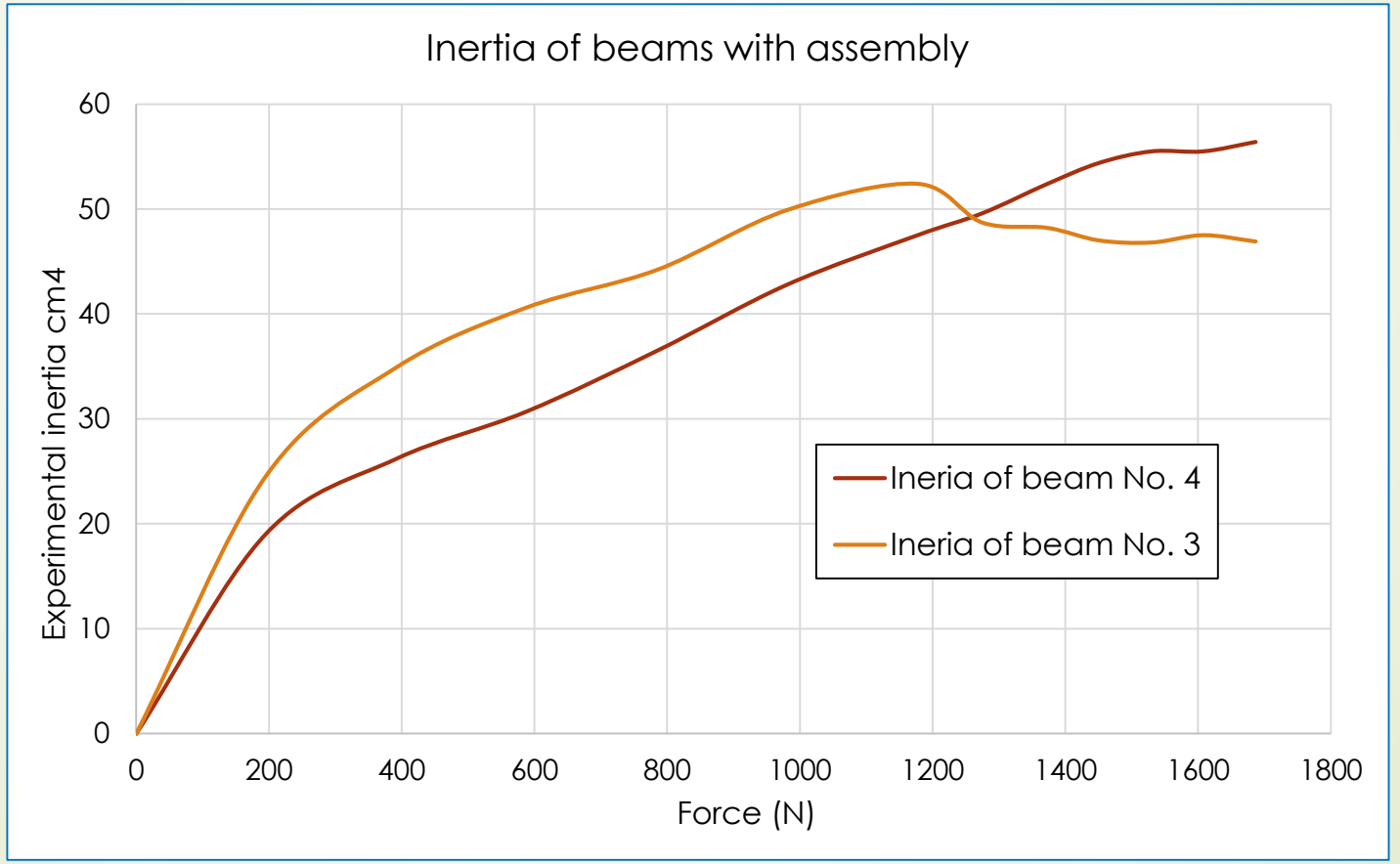
Experimental Inertia for beams with assembly



Assembly tests

- Shear test wood – wood.
- Speed test 2mm/mins.
- 2 Screws per side.
- Displacement sensor capacity of 10 mm.

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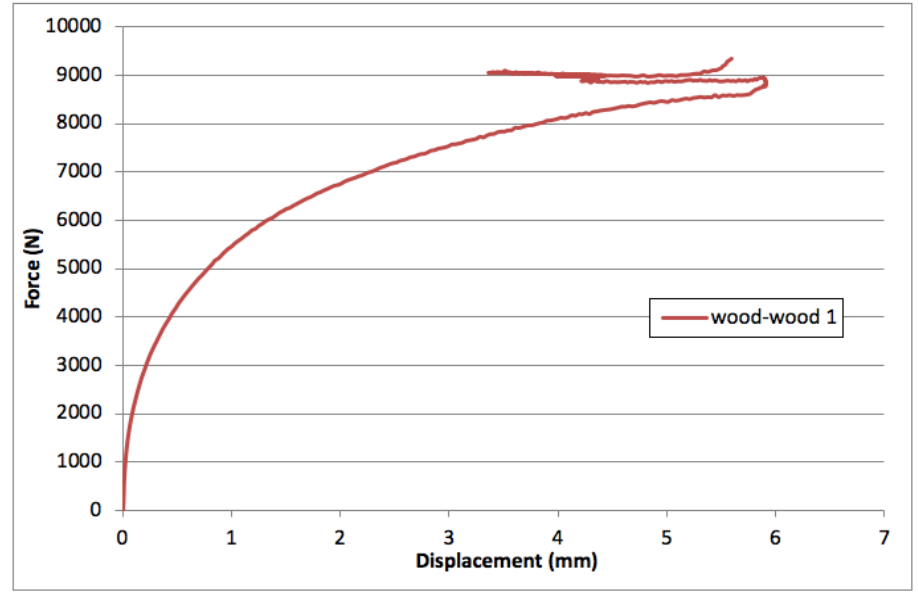
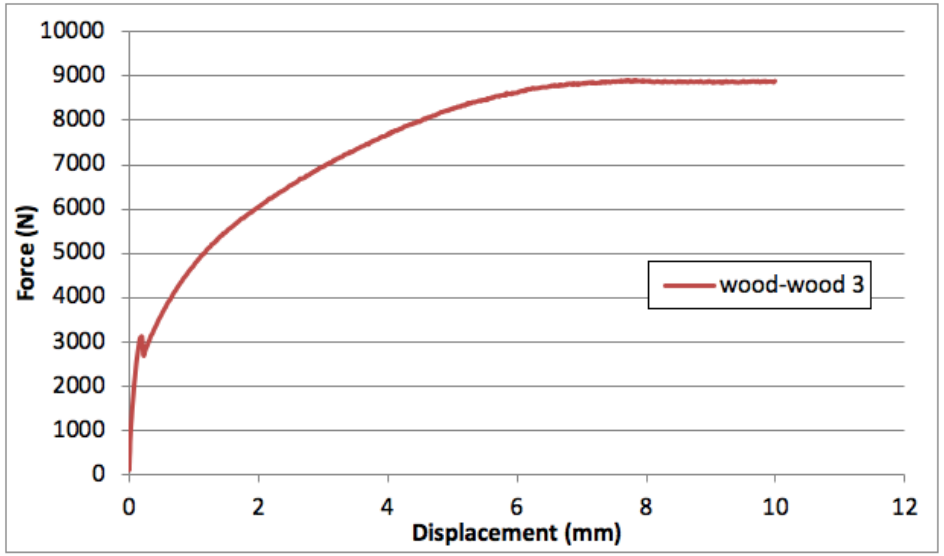
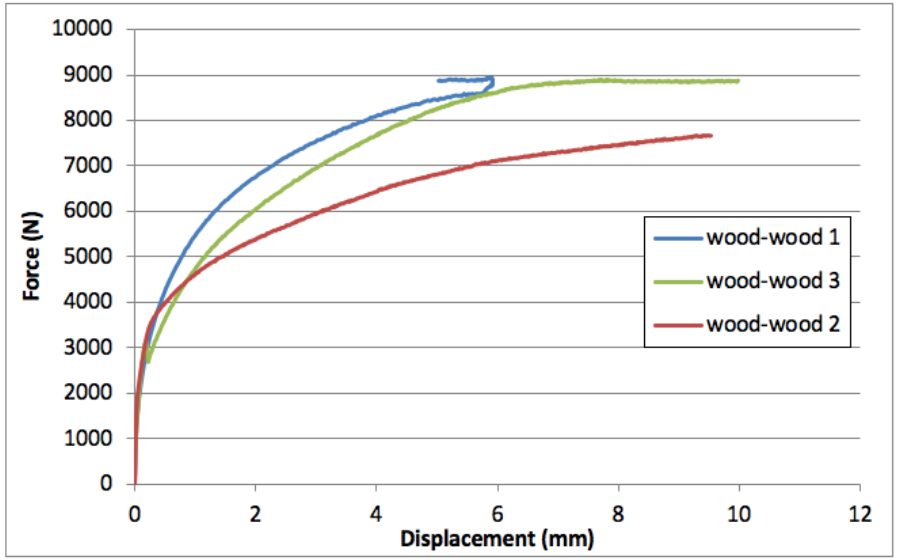
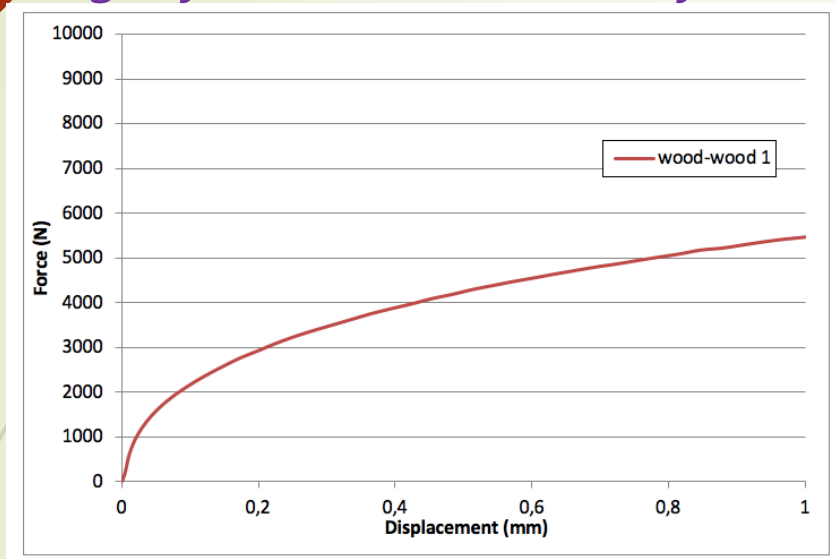


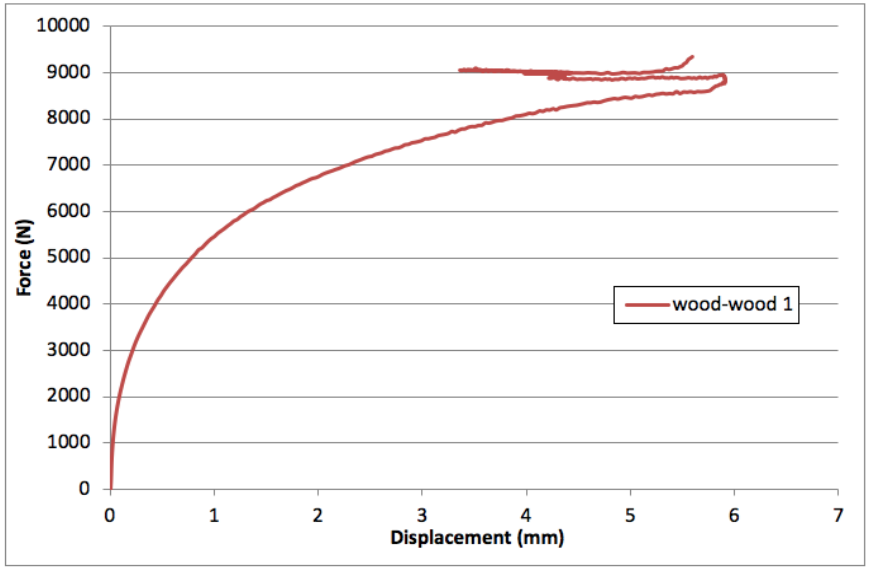




Rigidity of wood-wood assembly



Delta F	Delta S	K
463.4644775	0.047042126	9852.115811
860.8475342	0.097829889	8799.43276
667.0643311	0.072150765	9245.422854
360.036377	0.05232267	6881.078075
784.8684082	0.101494132	7733.140771
624.5756836	0.108671789	5747.358053
490.1791992	0.081067374	6046.565677
261.3005371	0.055910707	4673.533087
751.4797363	0.13697808	5486.13132
492.4060059	0.114551294	4298.563444
Average rigidity		**6876 KN/m**



Points Between 0.1 – 1 mm

Average rigidity K_{exp} = 6876 KN/m

$$K_{ser,theo} = \frac{\sqrt{\rho_{m1} \cdot \rho_{m2}}^{1.5} . d}{23} . n = \frac{\sqrt{640.420}^{1.5} . 3}{23} . 4 =$$

$$\mathbf{6159.2\ kN/m}$$

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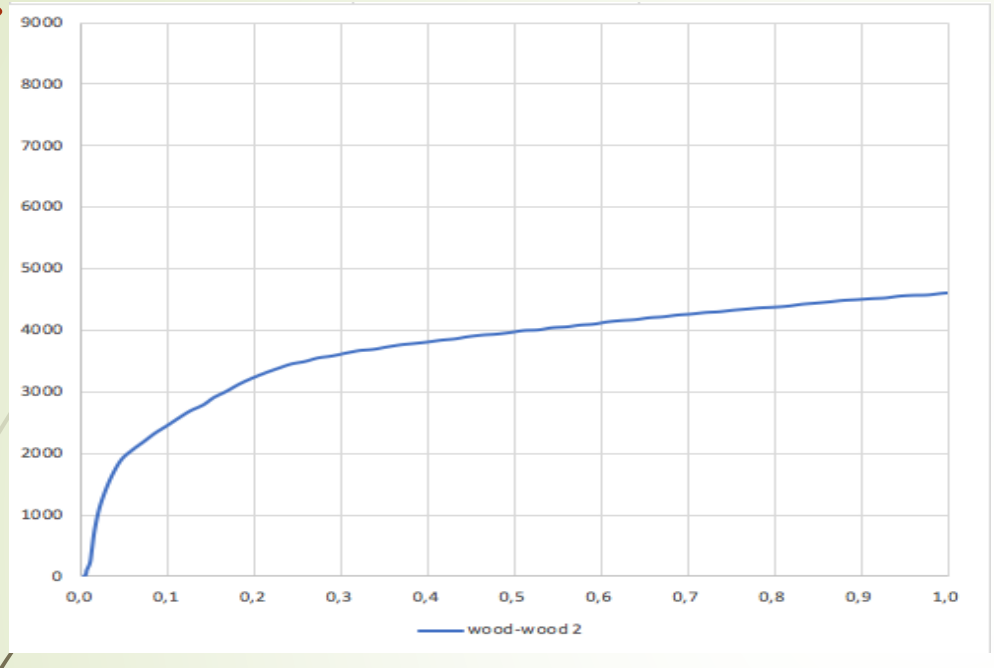

Delta F	Delta S	K
510.5380859	0.052670141	9693.121764
436.1279297	0.055259428	7892.371362
546.534668	0.10656123	5128.832179
846.8781738	0.093622679	9045.652019
946.6660156	0.107929569	8771.146083
596.0715332	0.06867716	8679.327058
763.8562012	0.116951473	6531.394469
676.138916	0.08198533	8247.071925
775.2780762	0.098607343	7862.275304
Average rigidity		8981

Average rigidity K_{exp} = 8981 KN/m

$$K_{ser,theo} = \frac{\sqrt{\rho_{m1} \cdot \rho_{m2}}^{1.5} . d}{23} . n = \frac{\sqrt{640.420}^{1.5} . 3}{23} . 4 =$$

$$\mathbf{6159.2\ kN/m}$$

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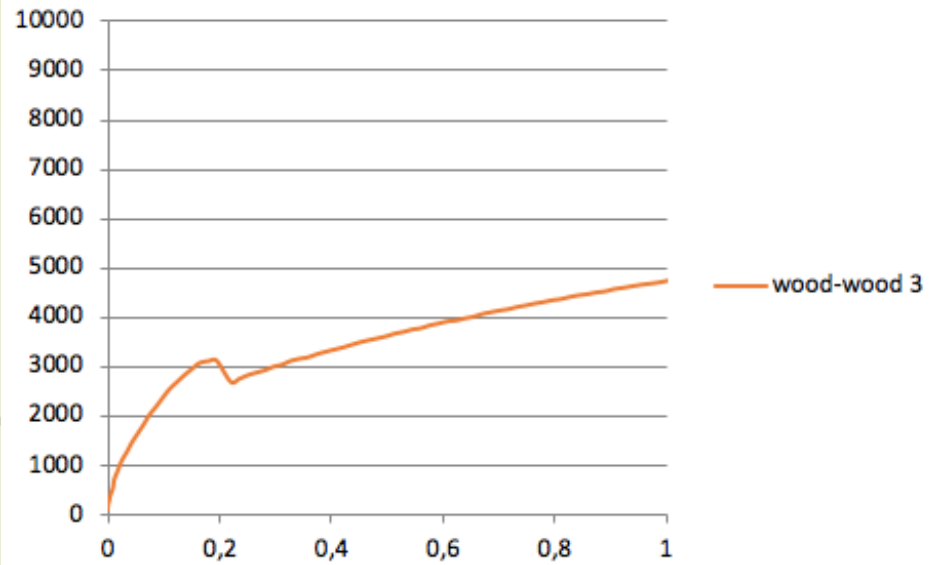

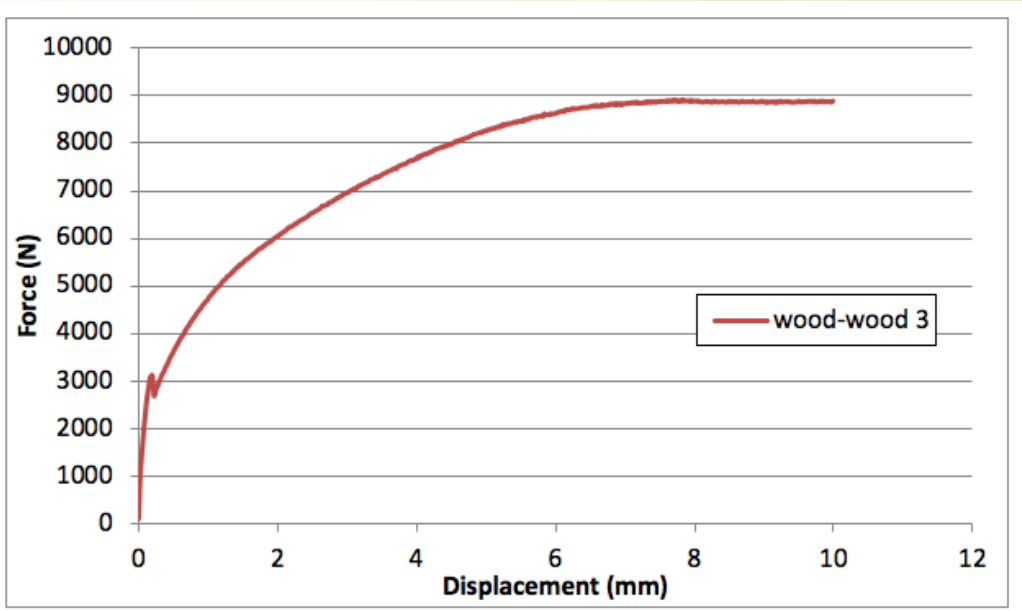

Delta F	Delta s	K
157.576416	0.046168629	3413.062522
139.4265137	0.045882261	3038.789048
142.776123	0.047080728	3032.581032
174.9667969	0.06283015	2784.758562
297.0029297	0.09205089	3226.507961
457.1694336	0.201961768	2263.643454
161.2995605	0.061479543	2623.629806
Average rigidity		2911

Average rigidity K_{exp} = 2911 KN/m

$$K_{ser,theo} = \frac{\sqrt{\rho_{m1} \cdot \rho_{m2}}^{1.5} . d}{23} . n = \frac{\sqrt{640.420}^{1.5} . 3}{23} . 4 =$$

$$6159.2\ kN/m$$

Total Average rigidity K_{exp} of wood wood assembly = (2911 + 8981 + 6876)/ 3 = 6256 KN/m

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- Shear test wood – Steel.
- Speed test 2mm/mins.
- 2 Bolts
- Displacement sensor capacity of 10 mm.

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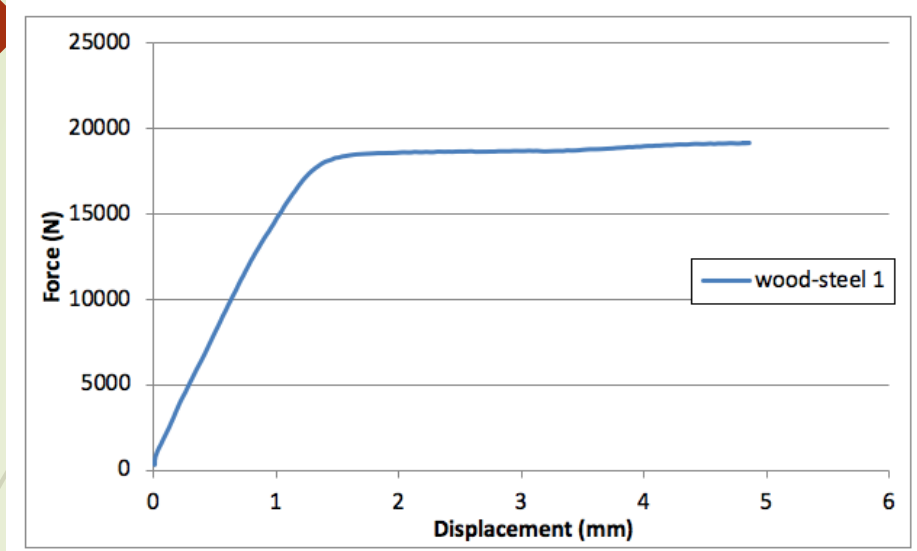

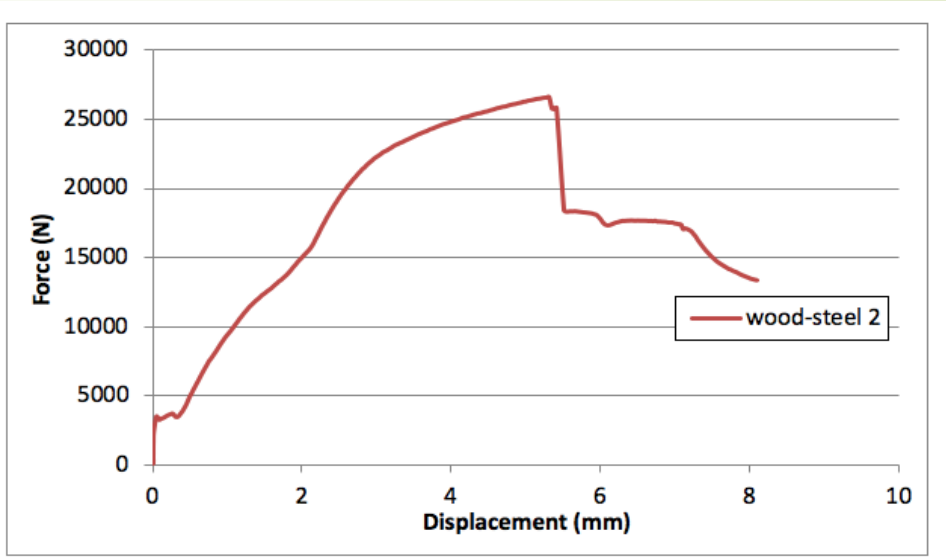

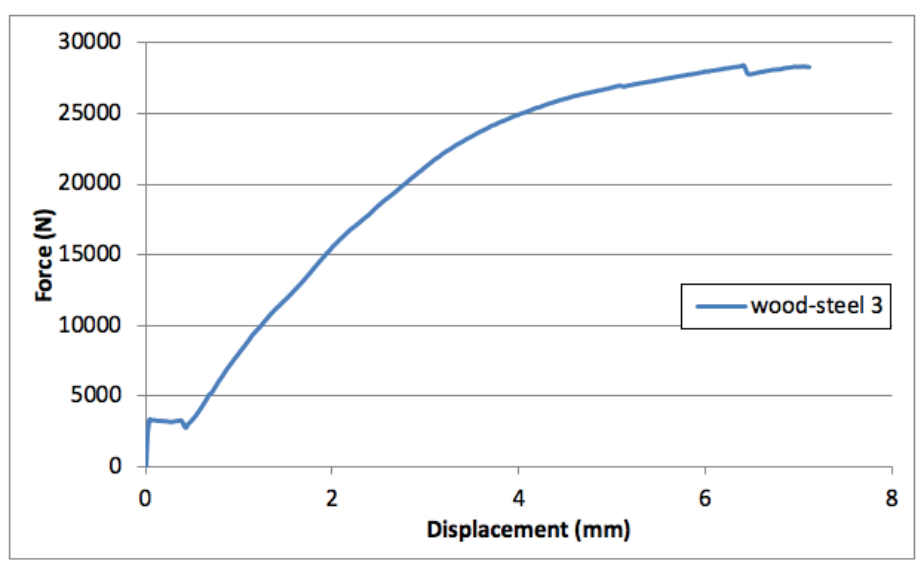

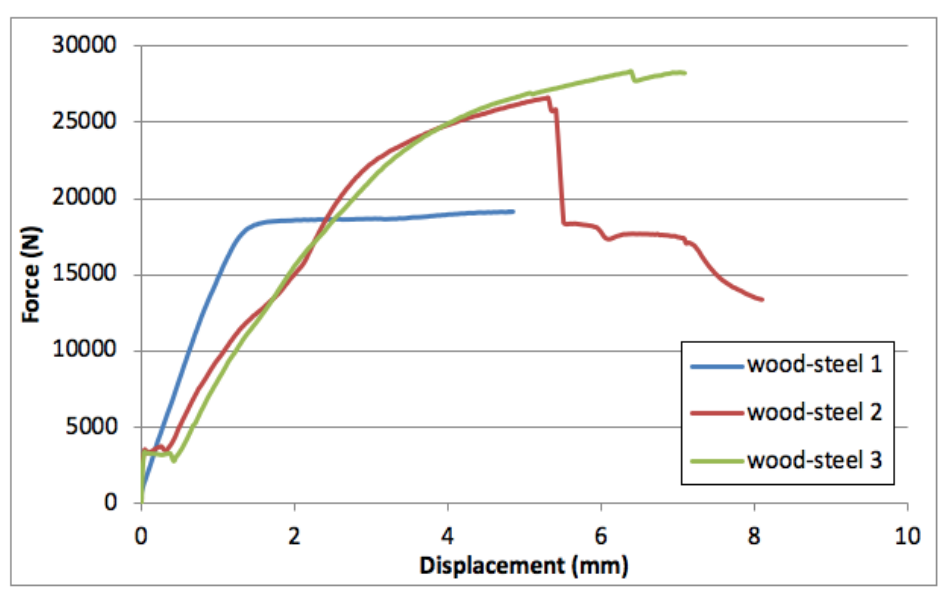

Rigidity of wood-Steel assembly

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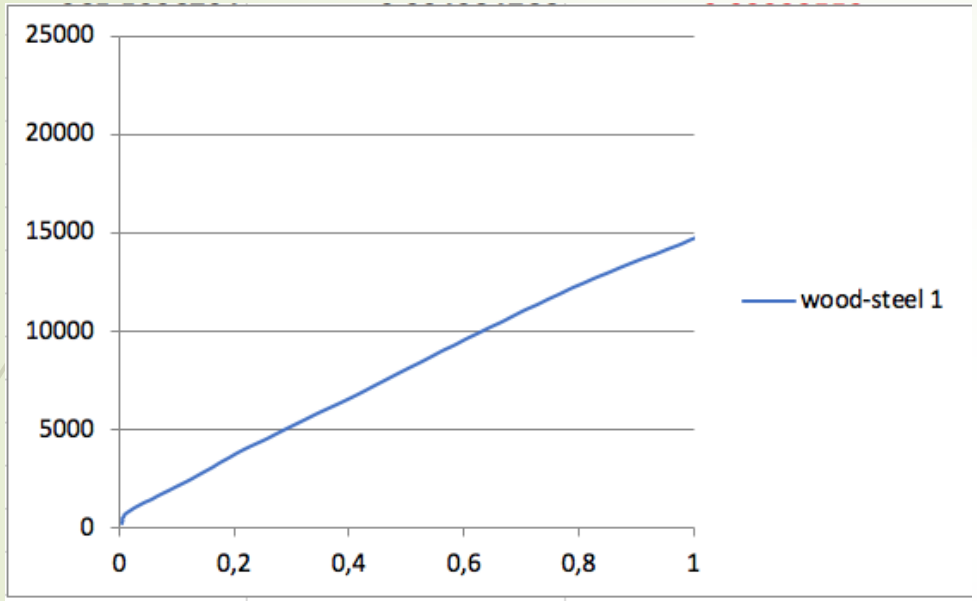

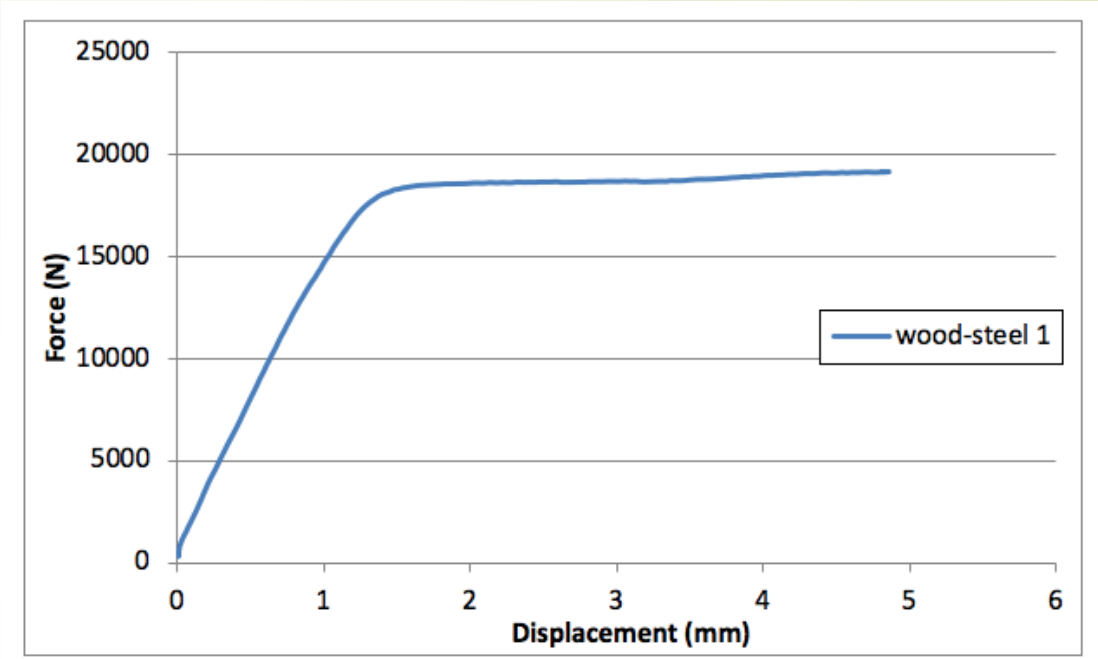

Delta F	Delta S	K
790.4125977	0.051142415	15455.12853
934.6252441	0.055921264	16713.23531
957.0202637	0.067102723	14262.01834
1047.176758	0.072108814	14522.17409
1112.651367	0.080111437	13888.7956
1192.275391	0.078857178	15119.42759
1774.975586	0.121022575	14666.48344
1455.176758	0.103045022	14121.75696
1102.981445	0.081382459	13553.06117
Average rigidity		14699

Average rigidity K_{exp} = 14699 KN/m

$$K_{ser,Bolts}\ \frac{\rho_m^{1.5}.d}{23} = \frac{640^{1.5}.5}{23}.2.\ 2 = 14079\ kN/m$$

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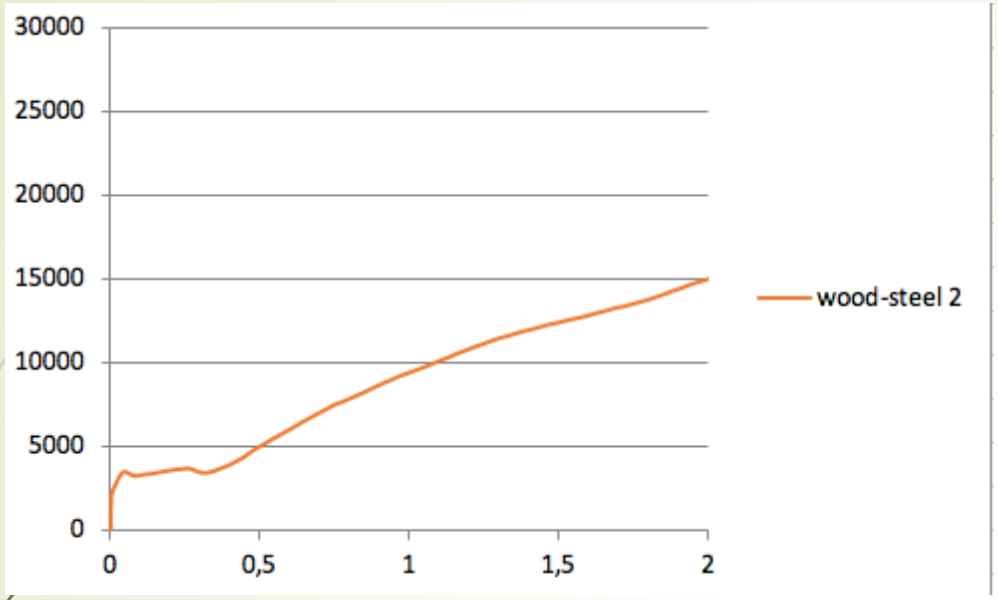

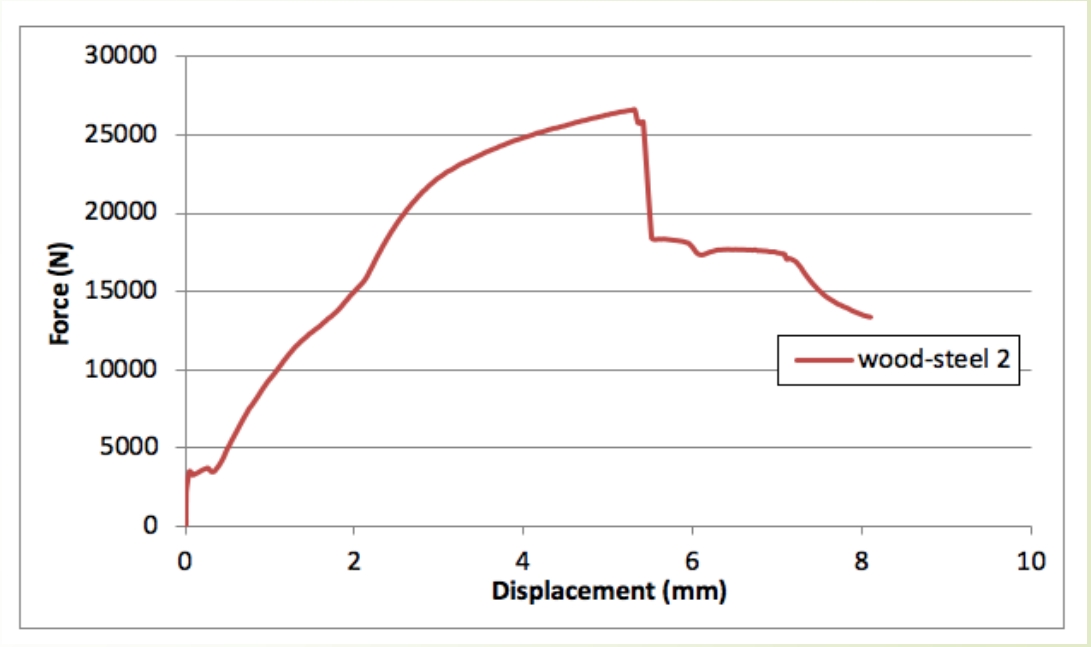

Delta F	Delta S	K
1073.831787	0.097677243	10993.67425
956.5327148	0.093660114	10212.80754
945.1811523	0.094754825	9975.018699
602.3725586	0.070348266	8562.720824
568.5898438	0.072786002	7811.802061
2030.364502	0.191337356	10611.43805
568.5898438	0.072786002	7811.802061
1164.734375	0.143268087	8129.754477
1175.749023	0.167120976	7035.316894
1985.189453	0.291240227	6816.329852
Average rigidity		8796

Average rigidity K_{exp} = 8796 KN/m

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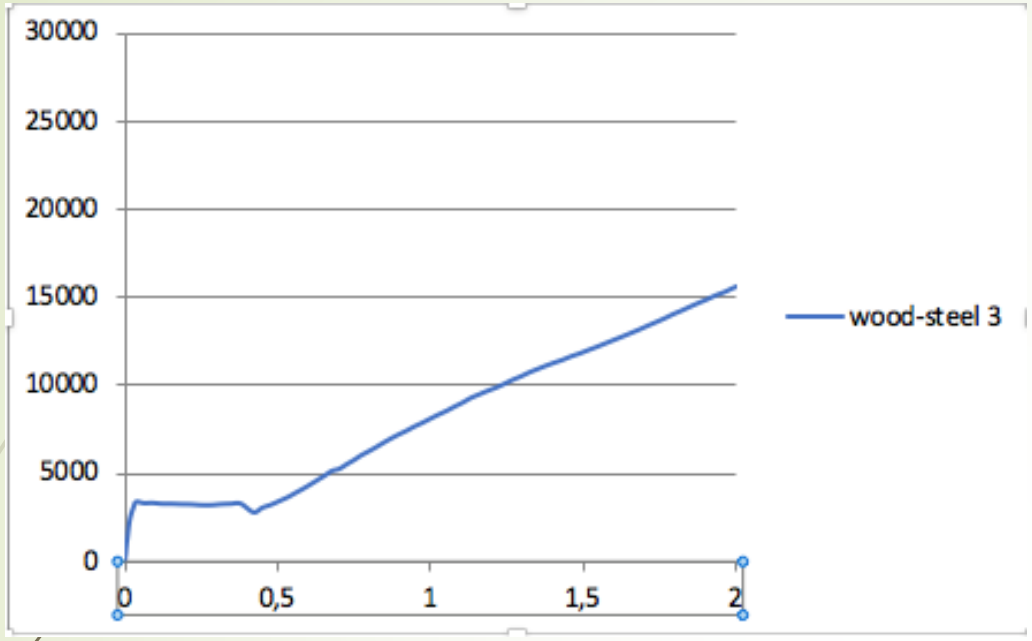

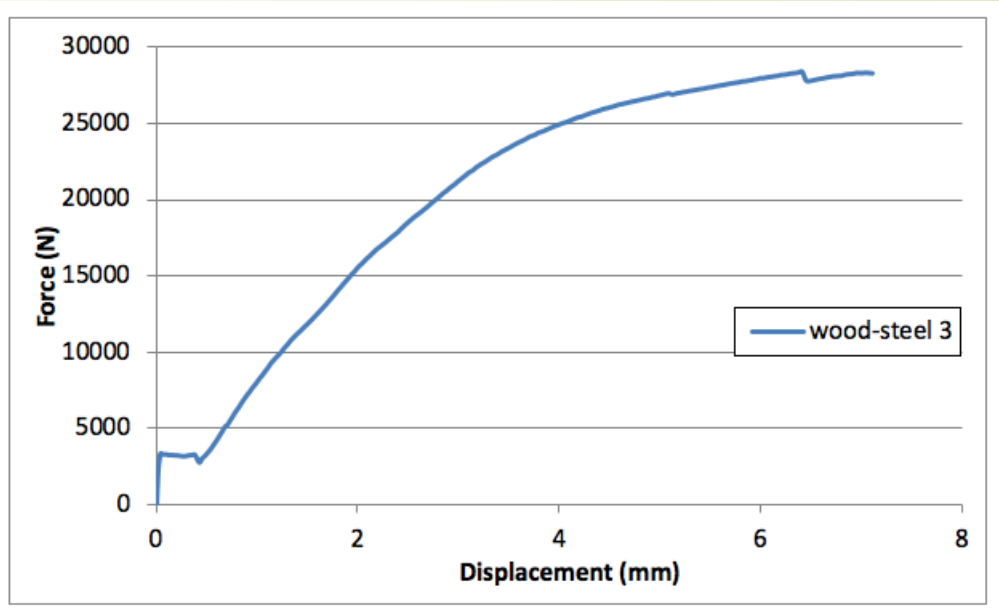

Delta F	Delta S	K
2083.415039	0.220016373	9469.36364
2136.290527	0.220732327	9678.195114
1130.974609	0.131903565	8574.25351
1289.371094	0.162672426	7926.181005
1376.237305	0.192314736	7156.171888
935.2509766	0.140226737	6669.562422
1656.619141	0.221675844	7473.16041
1665.388672	0.223882671	7438.667158
4219.705566	0.352635892	11966.18285
Average rigidity		8483

Average rigidity K_{exp} = 8483 KN/m

$$K_{ser,Bolts}\ \frac{\rho_m^{1.5}.d}{23} = \frac{640^{1.5}.5}{23}.2.\ 2 = 14079\ kN/m$$

Total Average rigidity K_{exp} of wood steel assembly K_{exp} = $\frac{14699+8796+8483}{3}$ = 10659 KN/m

Flexural test of steel connection

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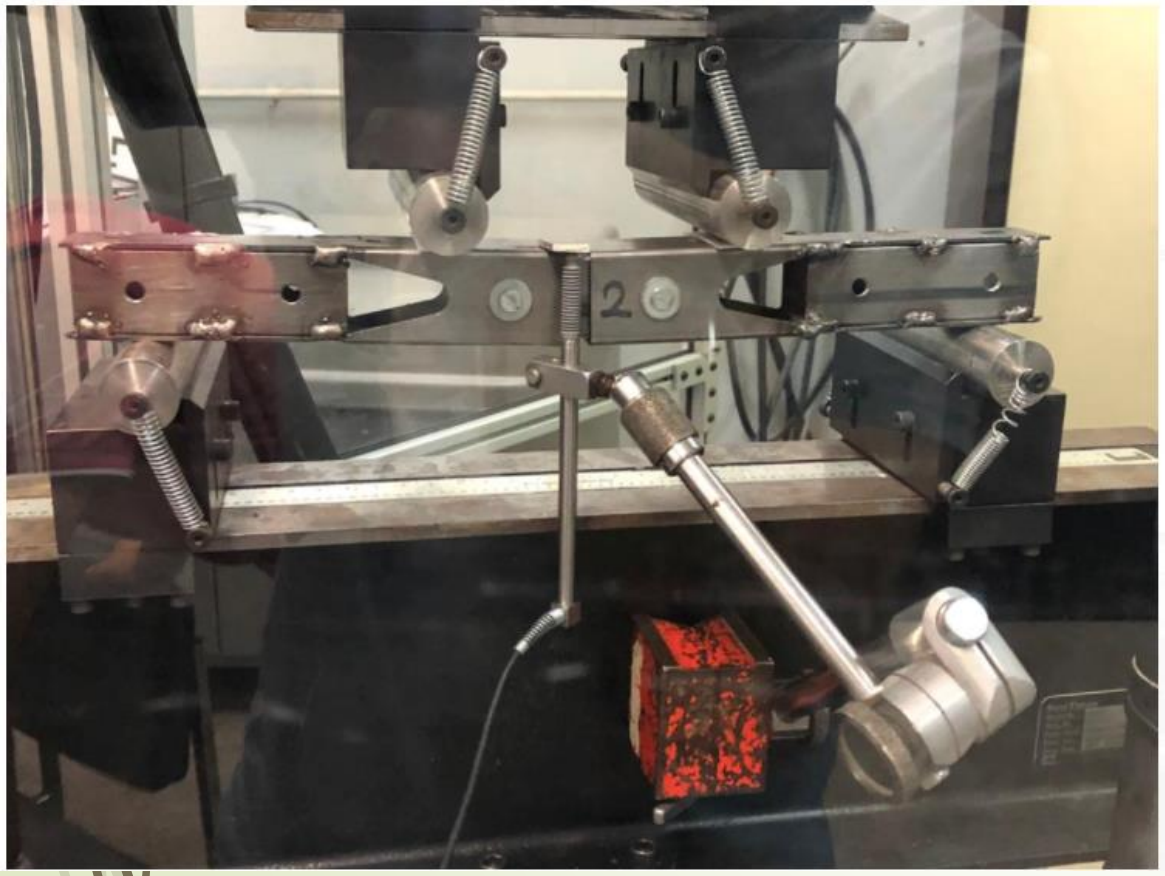

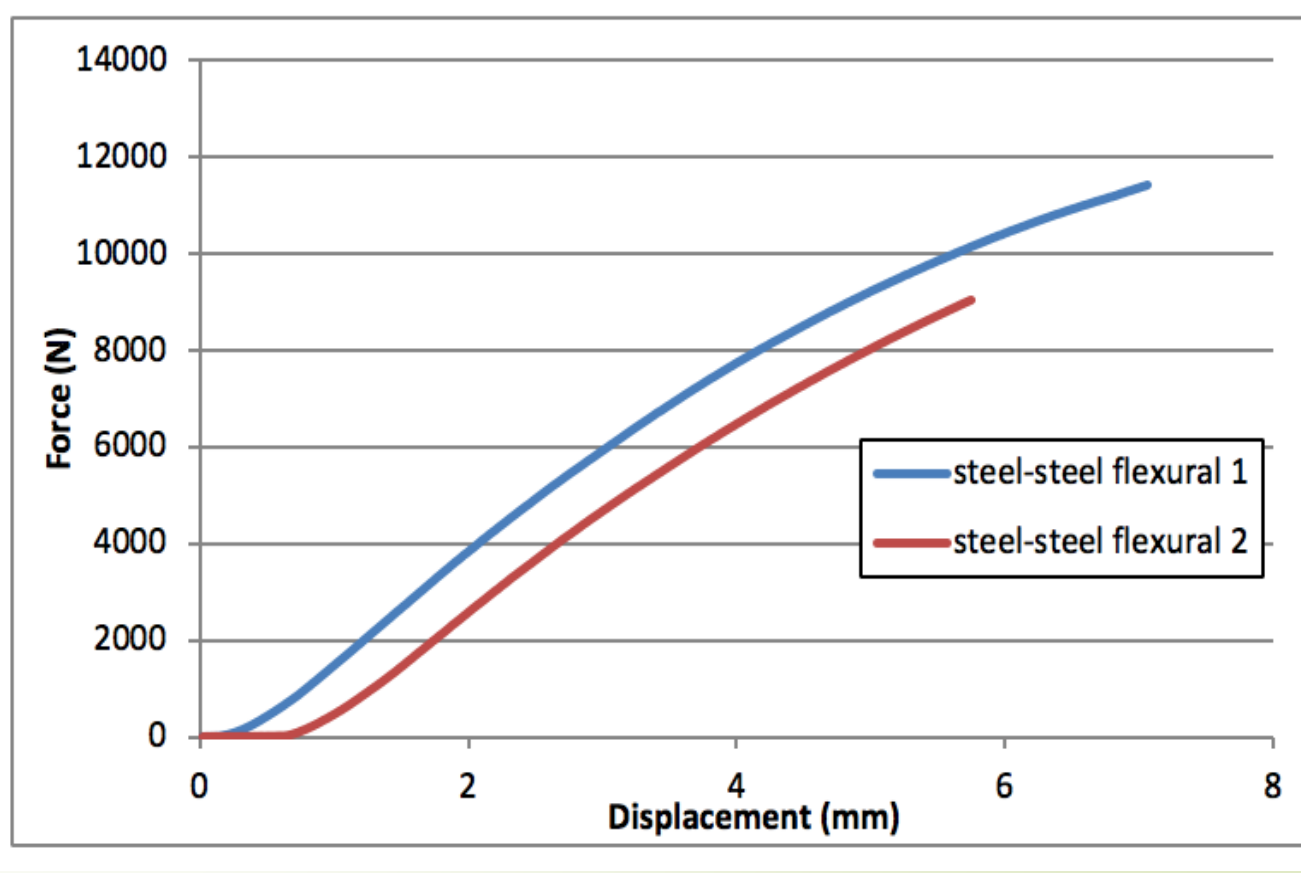

Length of assembly 38 cm

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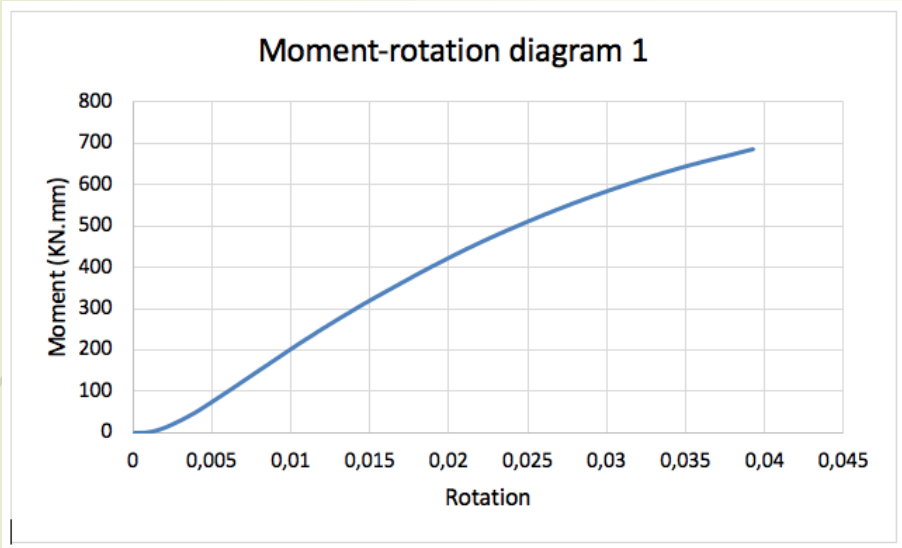
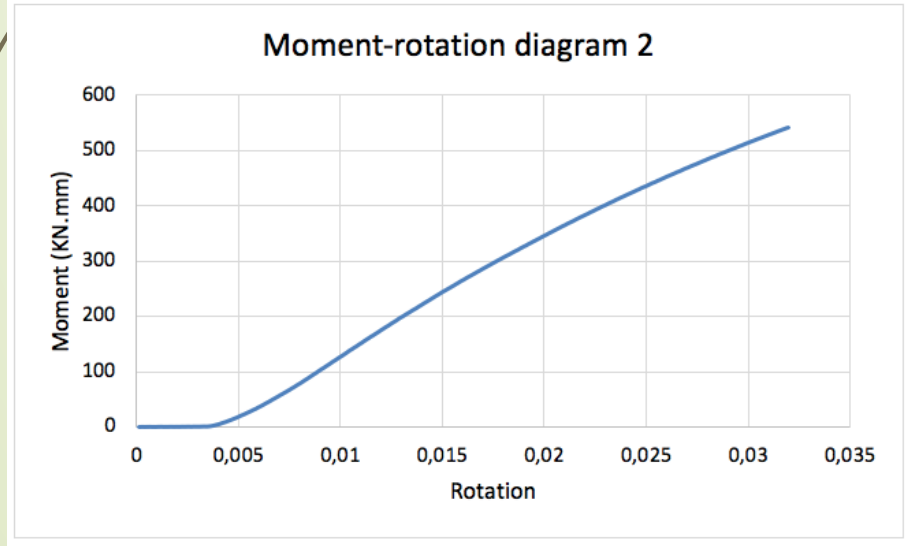
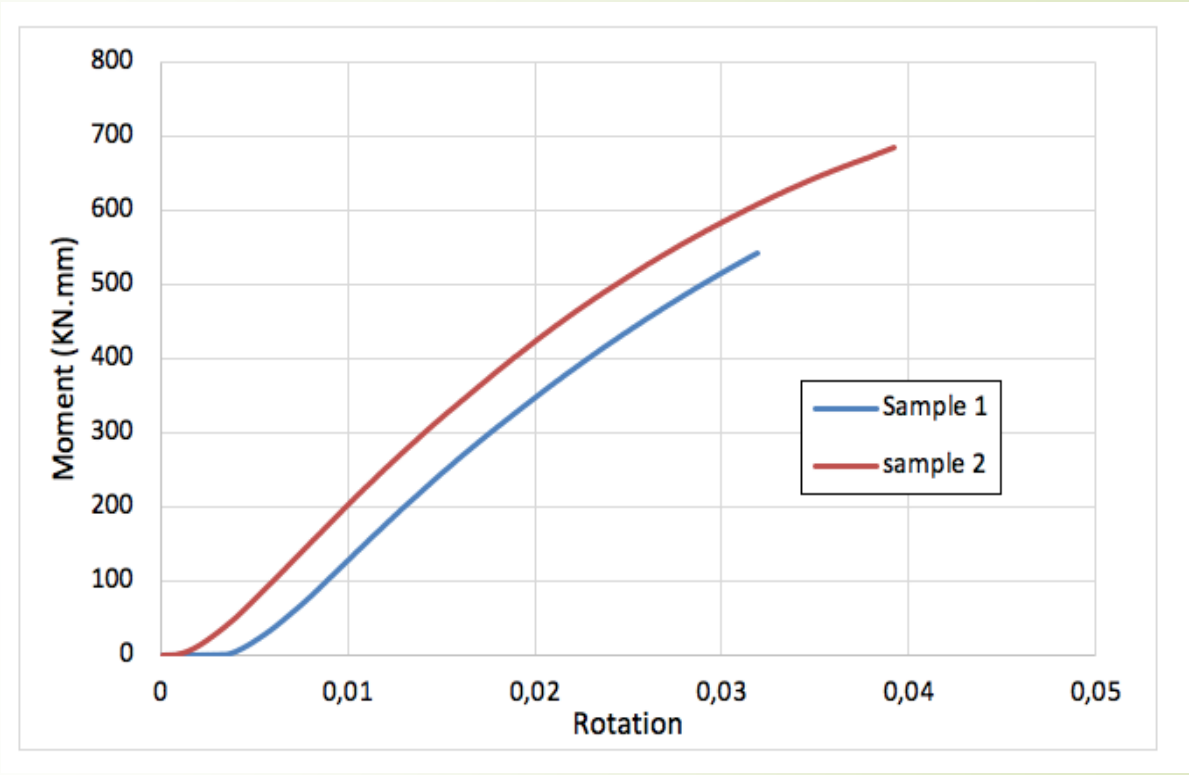






$The\ average\ Rigidity\ K_1$ = 22079 KN.mm

$The\ average\ Rigidity\ K_2$ = 24694 KN.mm

Average rigidity K_{exp} = $\frac{22079+24694}{2}$ = 23386 KN.mm

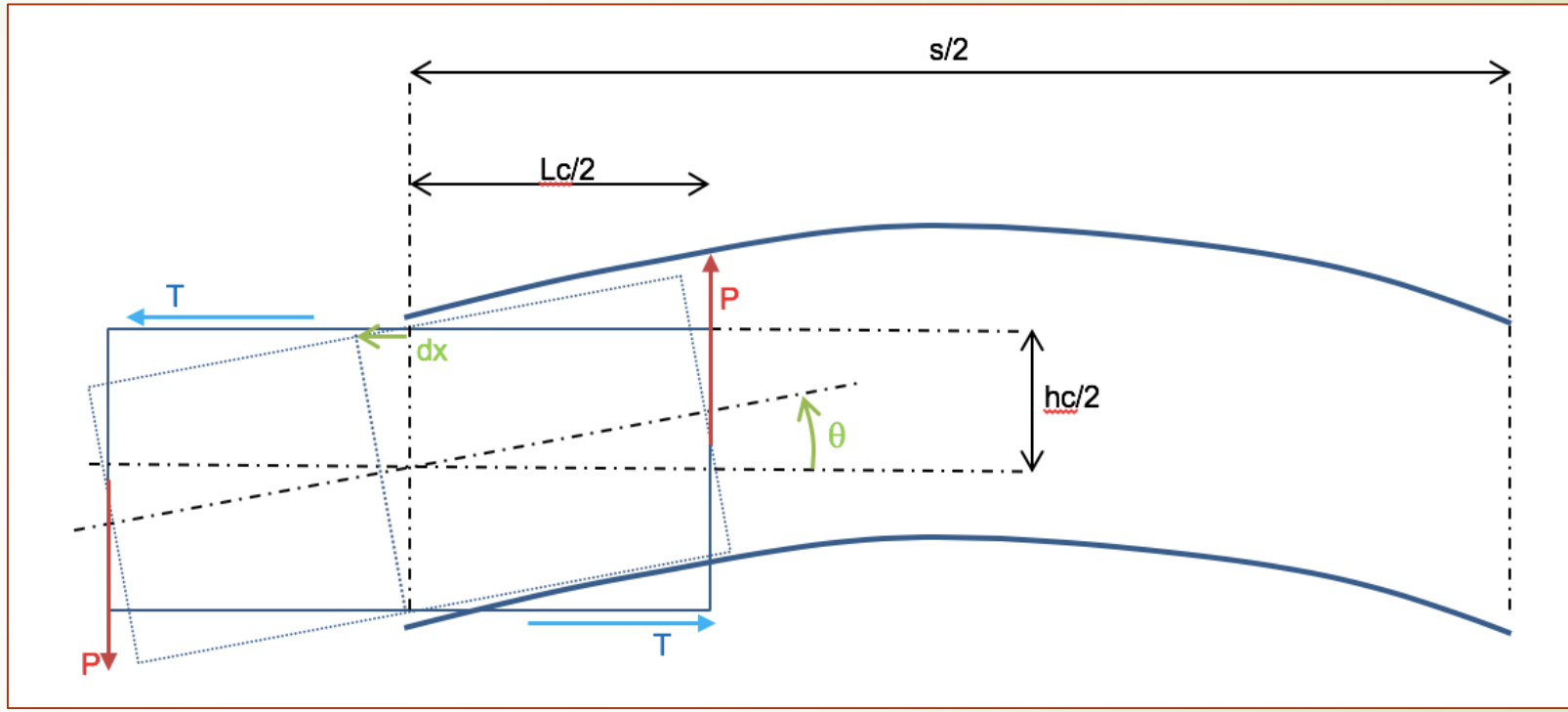
Tilting Rigidity (Basculement)

$$\frac{T}{Lc\,.e} = \frac{P}{hc\,.e}$$

$$P = T\,\frac{hc}{Lc}$$

With beam of 2 supports we can calculate the rotation at the support by:

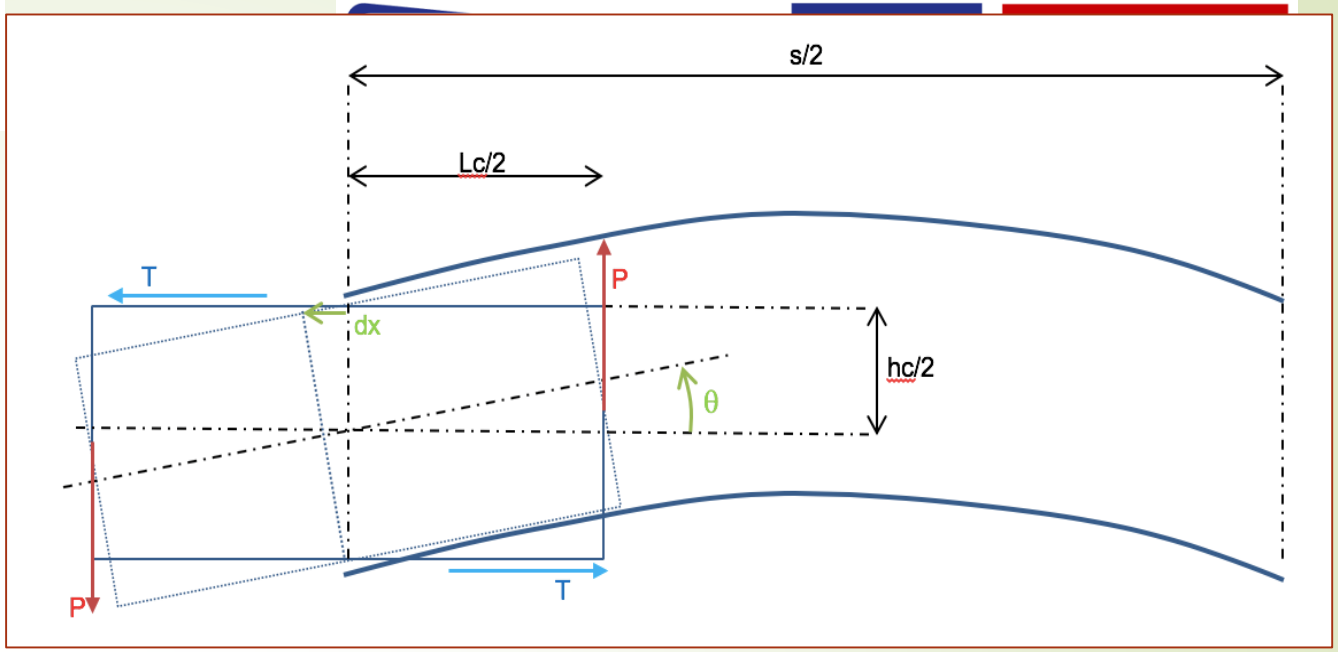
$$\theta = \frac{P.\frac{Lc}{2}.\left(\frac{s}{2}-\frac{Lc}{2}\right).\left(\frac{s}{2}+\frac{s}{2}-\frac{Lc}{2}\right)}{6.\left(\frac{s}{2}\right).E_{mean}.\left(2.\frac{b.e^3}{12}\right)}$$



S: distance between two shear blocks (cales) center to center.
Lc: The length of the shear block.
hc : the height of the shear block (distance between two lames)
b : length of the lame.
e: thickness of the lame.

Tilting Rigidity (Basculement)

$$\theta = \tan^{-1}\left(\frac{dx}{hc}\right) \approx \frac{dx}{hc} \rightarrow dx = \theta.\mathrm{hc}$$

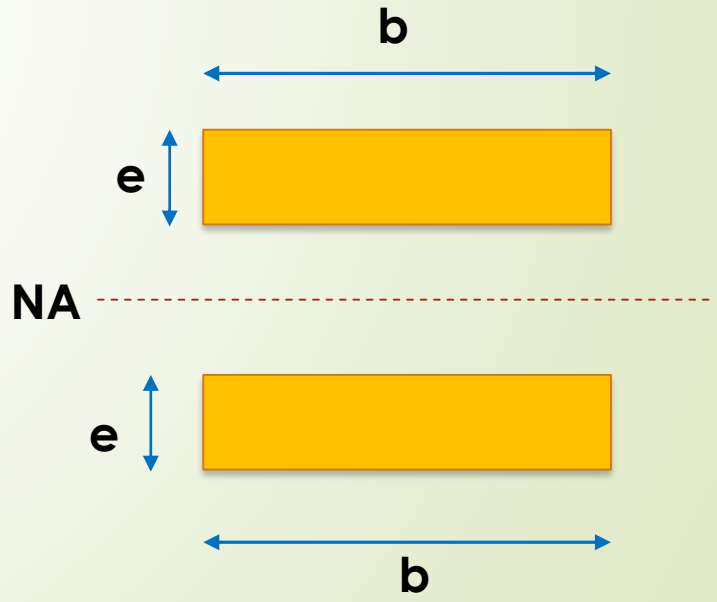


Then the equivalent rigidity (stiffness)

$$K_{u,E,bascule} = \frac{\mathrm{T}}{dx} = \frac{T}{\theta.hc} = \mathrm{T}.\left(\frac{3.s.E_{mean}.\left(\frac{b.e^3}{6}\right)}{P.\frac{Lc}{2}.\left(\frac{s}{2}-\frac{Lc}{2}\right).\left(s-\frac{Lc}{2}\right)}\right).\left(\frac{1}{hc}\right)$$

$$K_{u,E,bascule} = \mathrm{T}.\left(\frac{s.E_{mean}.\frac{b.e^3}{2}}{\left(\mathrm{T}.\frac{hc}{Lc}\right).\frac{Lc}{2}.\left(\frac{s}{2}-\frac{Lc}{2}\right).\left(s-\frac{Lc}{2}\right)}\right).\left(\frac{1}{hc}\right)$$

$$K_{u,E,bascule} = \frac{s.E_{mean}.b.e^3}{hc^2.\left(\frac{s}{2}-\frac{Lc}{2}\right).\left(s-\frac{Lc}{2}\right)}$$



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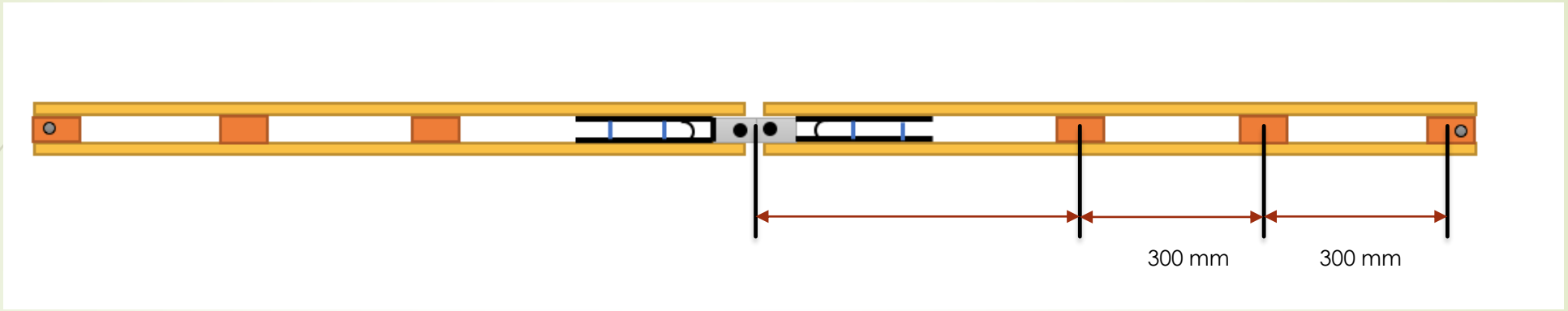
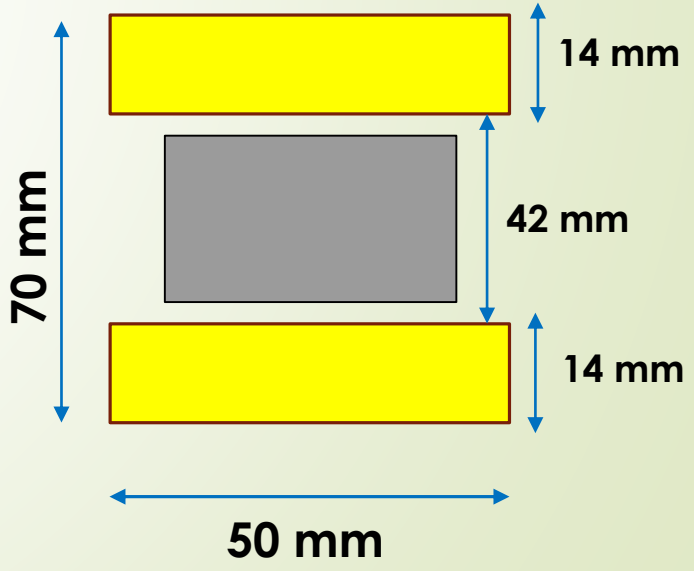


$$K_{u,E,bascule} = \frac{s.E_{mean}.b.e^3}{hc^2.\left(\frac{s}{2}-\frac{Lc}{2}\right).\left(s-\frac{Lc}{2}\right)}$$

$$K_{u,E,bascule} = \frac{300 \text{ x } 11000 \text{ x } 50 \text{ x } 14^3}{42^2.\left(\frac{300}{2}-\frac{100}{2}\right) \text{x} \left(300 -\frac{100}{2}\right)}$$

$$K_{u,E,bascule} = 10266 \text{ KN/m}$$

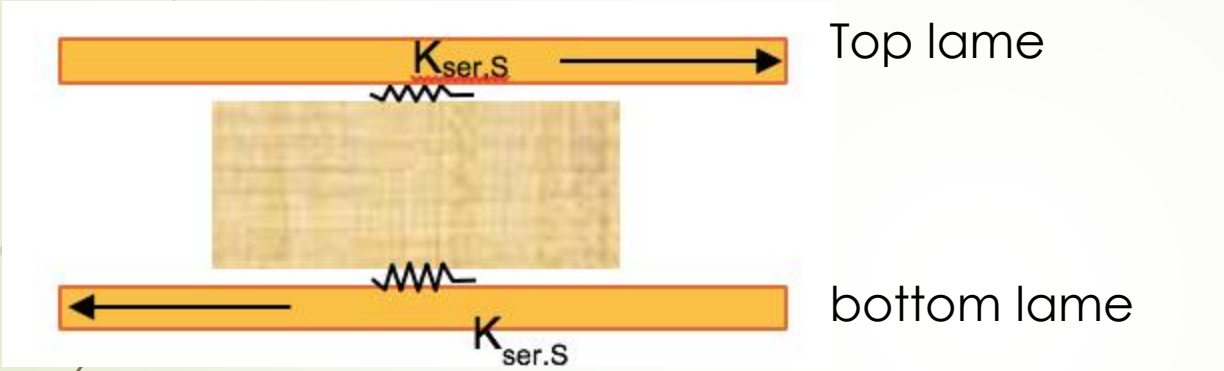


Combination of rigidities

- Shear block (wedges) cale de cisaillement

→ Shear wood/wood

→ Tilting (basculement)



Top lame

bottom lame

$$K_{u,\text{Bascul},CI} = \left[\frac{1}{\frac{1}{K_{u,O,\text{top},CI}} + \frac{1}{2.K_{u,BASC,CI}}} = \frac{1}{\frac{1}{K_{u,O,\text{bottom},CI}} + \frac{1}{2.K_{u,BASC,CI}}} \right]$$

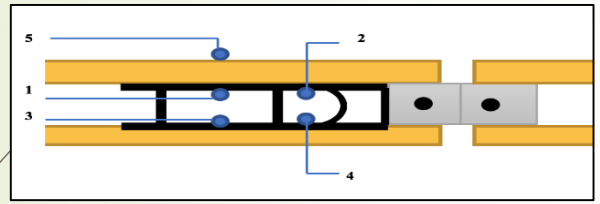
$$K_{u,\text{Bascul},CI} = \left[\frac{1}{\frac{1}{3128} + \frac{1}{2\ x\ 10266}} = \frac{1}{\frac{1}{3128} + \frac{1}{2\ x\ 10266}} \right] = 2715\ \ kN/m$$

$$K_{u,\text{Bascul},CI} = 2715 \text{ x } 6 \text{ Cales} = 16290 \text{ KN/m}$$

Combination of rigidities

- Shear wood/wood
- Tilting (basculement)
- Shear wood/steel

❖ cale de cisaillement et assemblage bois/acier



$K_{u,assem\ b.a}$ = 10659 x 2 assemblages = 21318 KN/m

$$K_{u,\text{Bascul},CI,assem\ b.a} = \left[\frac{1}{\frac{1}{K_{u,O,\text{top},assem\ b.a}} + \frac{1}{K_{u,BASC,CI}}} = \frac{1}{\frac{1}{K_{u,O,\text{bottom},assem\ b.a}} + \frac{1}{K_{u,BASC,CI}}} \right]$$

$$K_{u,\text{Bascul},CI,assem\ b.a} = \left[\frac{1}{\frac{1}{10659} + \frac{1}{16290}} \right] = 6443 \text{ KN/m} \quad (\text{ for the entire beam})$$

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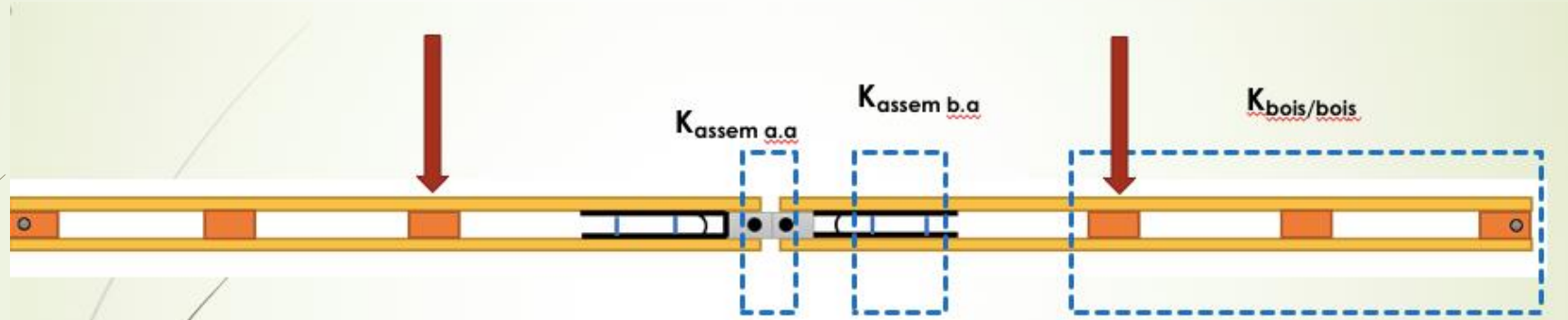
Combination of rigidities



$K_{u,\text{Bascul},CI,assem\ b.a} = 6443$ KN/m (for the entire beam)

Rotational rigidity $K_{\text{assemb a.a}} = 23386$ KN.mm (for the entire beam

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