Innovative Timber Composites:
Improving wood with other materials

17 October 2013 – Nicosia, Cyprus

Enhanced timber properties with FRP composites

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Background
Issues/problems

- Poor performance of glulam beams in bending
- Low stiffness
  - Beam size/depth
- Poor long-term behaviour
  - Large reduction in MOE due to creep values
- Low ductility
  - Sudden brittle failures

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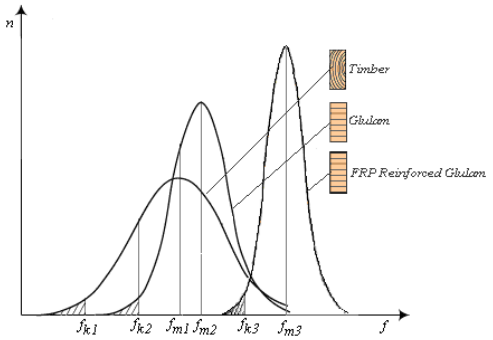
COST FP1004 – Enhance mechanical properties of timber, engineered wood products and timber structures

Background

Effects and opportunities

- Increased stiffness
- Lower variability
- Higher ductility



Background

Scope of this presentation

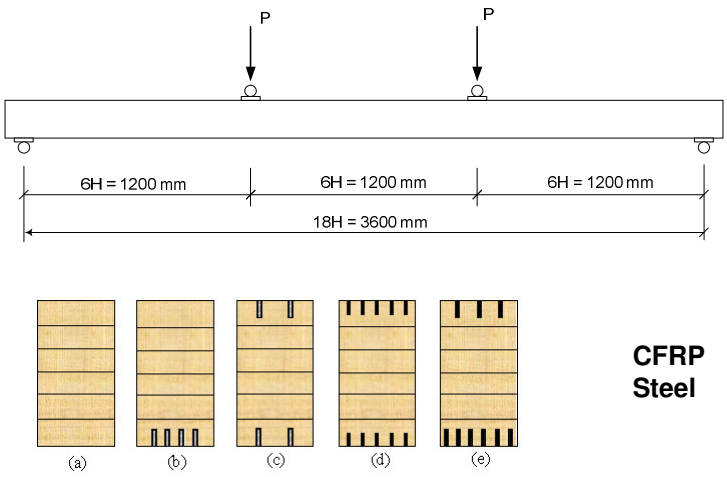
Four studies to be presented:

- **Strengthening of glulam beams**
- **Strengthening timber for long-term performance**
- **Strengthening the compression side of a beam**
- **Strengthening glulam beams with pre-stressed FRP**

Strengthening glulam beams
First study - objectives

- Identify and optimise effective ways to maximise strength/stiffness properties
- Identify possible failure modes
- Compare steel with CFRP as reinforcement for strengthening glulam
- Identify opportunity to induce ductility

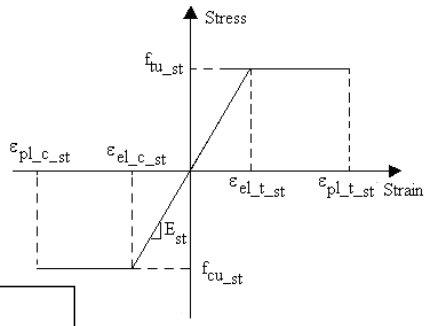
Strengthening glulam beams
First study - tests



Strengthening glulam beams
First study - reinforcements

Steel

- Steel plates (30 x 4 mm)
- Material model
  - Linear-elastic – elastic-plastic
  - Tension and compression



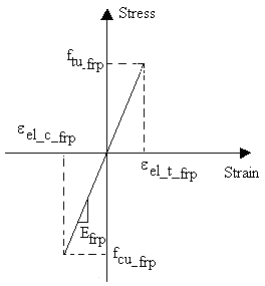
Property	Value
Yield Strength (fyk)	*275-300 N/mm²*
Modulus of elasticity	*210 000 N/mm²*

Strengthening glulam beams
First study - reinforcements

CFRP (Carbon Fibre Reinforced Polymers)

- Sika CarboDur S
  - High strength
- Sika CarboDur H
  - High stiffness
- Material model
  - Linear-elastic

Elastic Modulus	
Sika CarboDur S	*165,000 N/mm²*
Sika CarboDur H	*300,000 N/mm²*
Tensile Strength*	
Sika CarboDur S	*2,800 N/mm²*
Sika CarboDur H	*1,300 N/mm²*



Strengthening glulam beams
First study - reinforcements

Adhesives

- **Sikadur 30**
  - Cement paste-like
  - Dense, less viscous

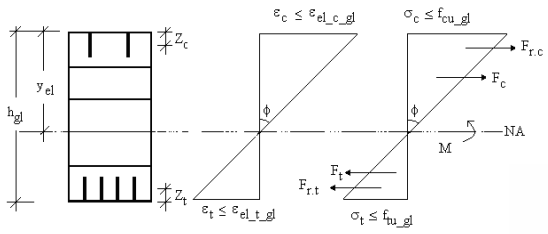
Sikadur 30	
Density	*1.77 kg/L (A + B)*
*Shear strength**	*15 MPa*
*E-Modulus**	*12,800 MPa*

- **Sikadur 330**
  - Paste-like
  - Viscous

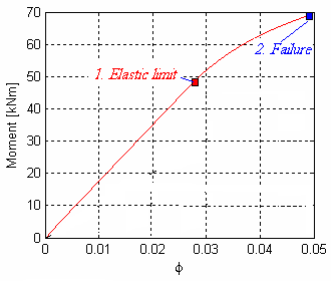
Sikadur 330	
Density	*1.31 kg/L (A + B)*
*Shear strength**	*10 MPa*
*E-Modulus**	*3800 MPa*

Strengthening glulam beams
First study - non-linear model

Linear-elastic phase



Glulam
f_t = 44 MPa
f_c = 46 MPa
E = 13.5 GPa

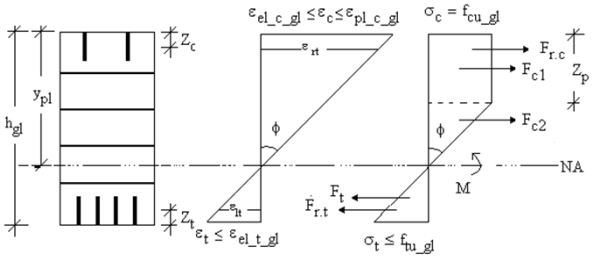


- Timber is linear elastic
- Yielding of reinforcement is considered

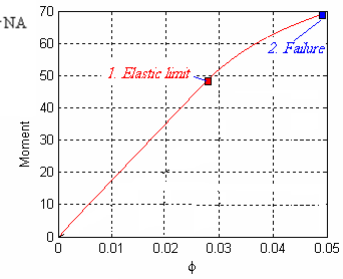
Strengthening glulam beams

First study - non-linear model

Plastic phase



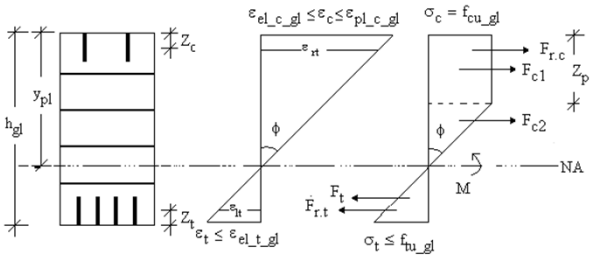
CFRP
f = 2800 or 1300 MPa
E = 165 or 300 GPa



- Timber plasticises
- Yielding of reinforcement is considered

Strengthening glulam beams

First study - Non-linear model



CFRP
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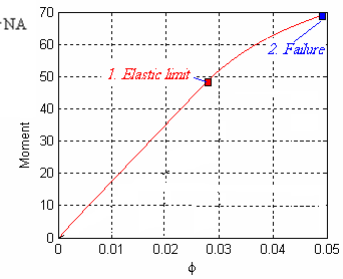
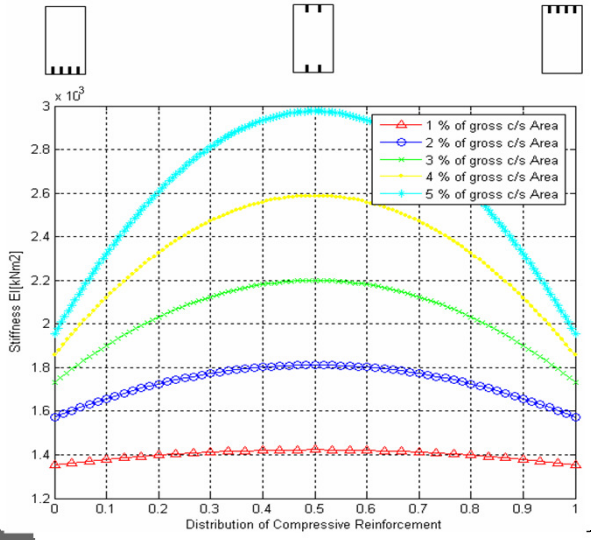


- Timber plasticises
- Yielding of reinforcement is considered

COST FP1004 – Enhance mechanical properties of timber, engineered wood products and timber structures

Strengthening glulam beams

First study - non-linear model - change in stiffness



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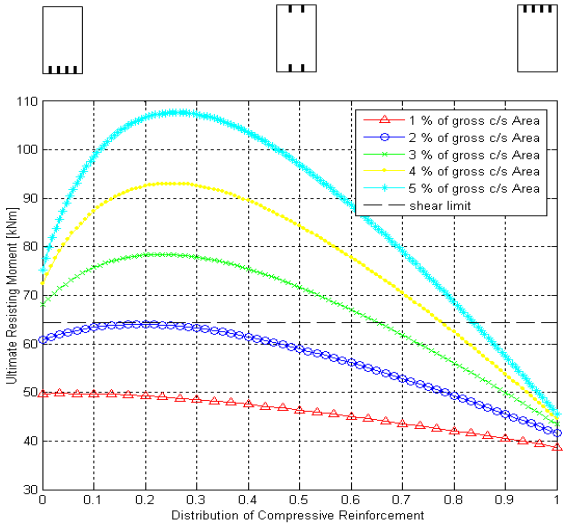
Strengthening glulam beams

First study - non-linear model - change in moment capacity



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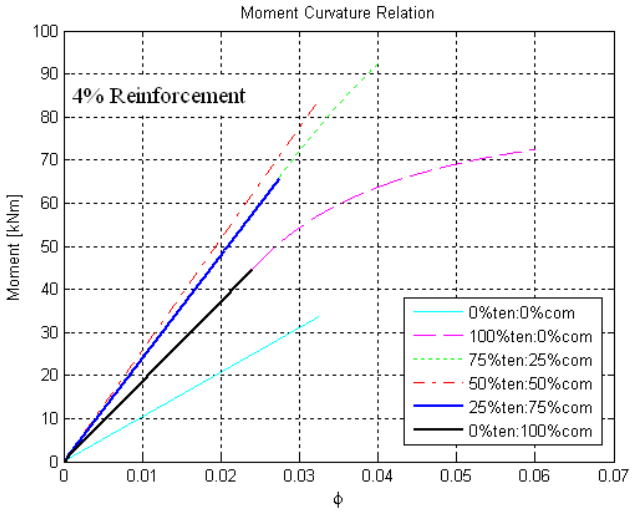
Strengthening glulam beams

First study - non-linear model - moment - curvature



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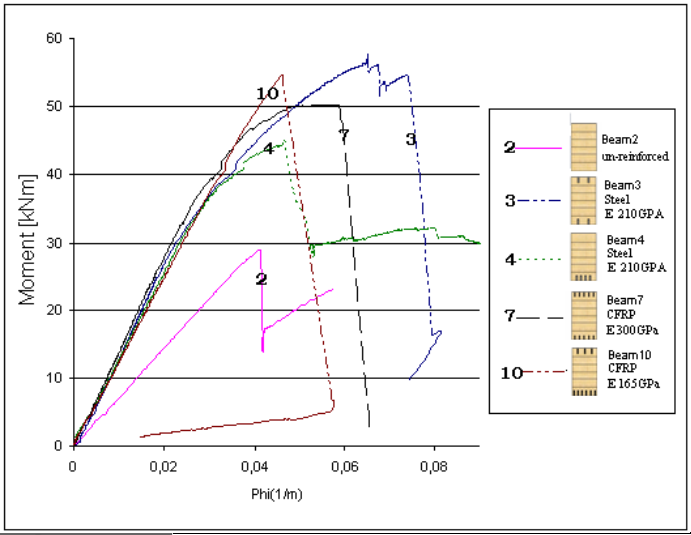
Strengthening glulam beams

First study – experimental results



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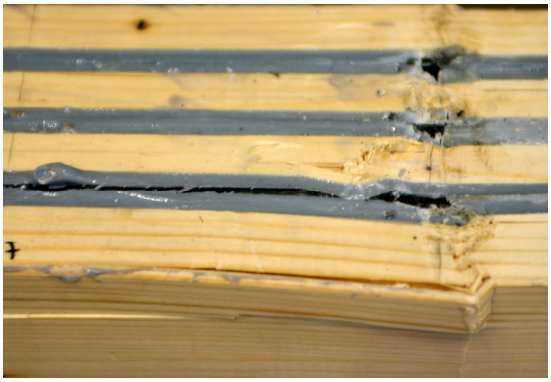
Strengthening glulam beams

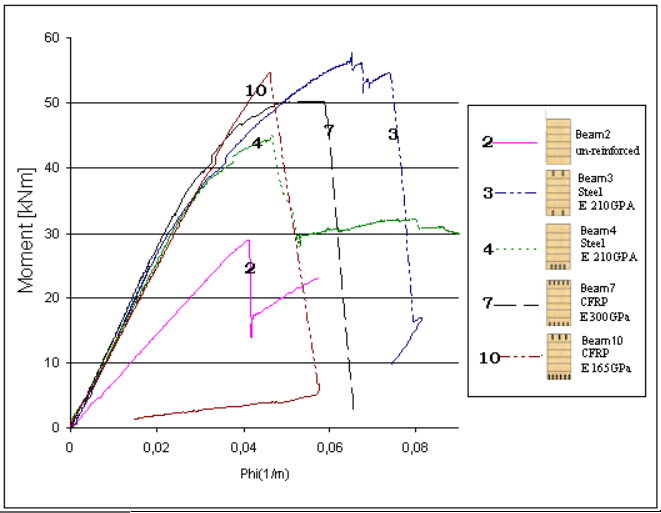
First study – experimental results

Buckling of CFRP



Strengthening glulam beams

First study – experimental results



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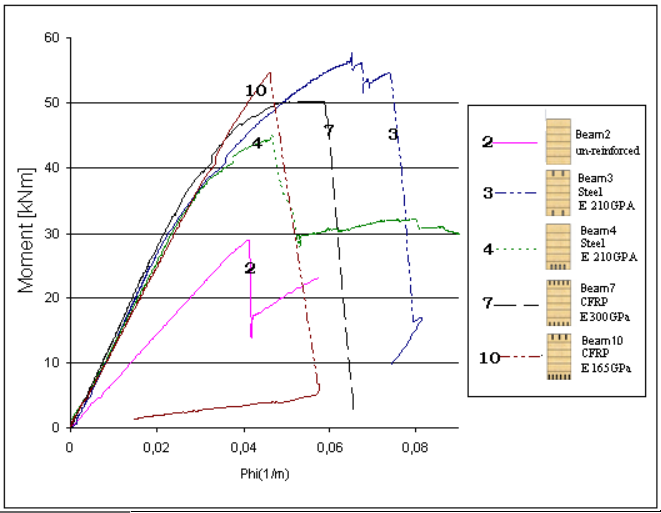
Strengthening glulam beams

First study – experimental results

Shear failure in glulam

Strengthening glulam beams

First study – experimental results



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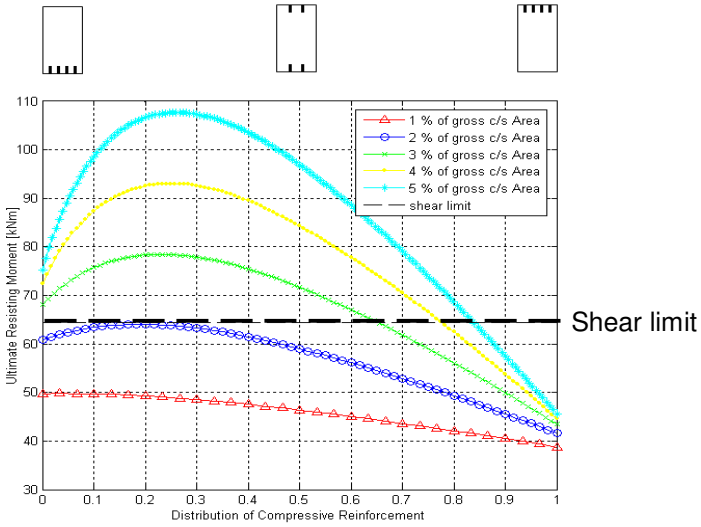
Strengthening glulam beams

First study – conclusions

- Higher stiffness and higher moment capacity can be obtained
- Amount and position of reinforcement determine the behaviour of the beam
  - Ductility
  - Failure modes
  - Strength
  - Stiffness
- Results from model and tests agreed

Strengthening glulam beams

First study - non-linear model - change in moment capacity



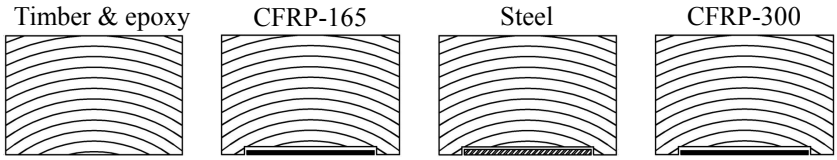
Shear limit

Strengthening for long-term performance

Second study: creep test – timber specimens

4 types of beam with 6 specimens in each

In all, 24 specimens, pine sapwood, 45 x 70 x 1100 mm³



Beam type	Reinforcement	Size	E-modulus	Tensile strength
1	-	-	-	-
2	CFK 150/2000	70 mm²	165 GPa	2310 MPa
3	CarboDur H514	70 mm²	300 GPa	1350 MPa
4	Steel	100 mm²	210 GPa	235 MPa

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Strengthening for long-term performance

Second study: creep test – timber specimens

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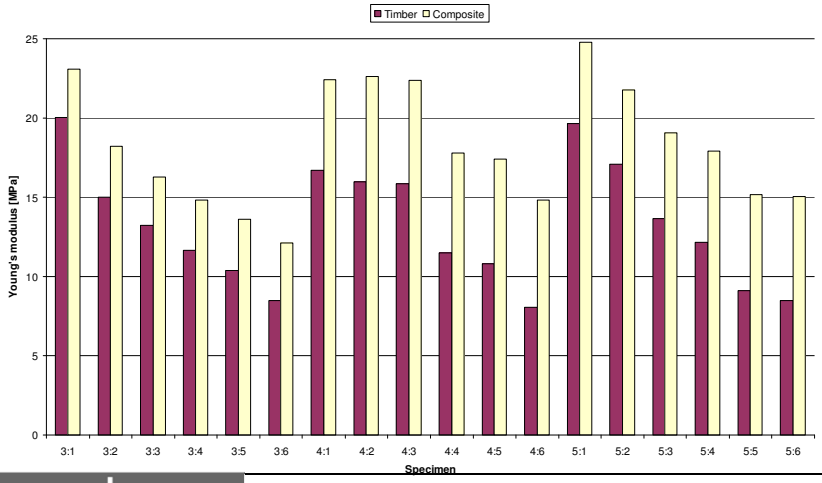
Strengthening for long-term performance

Second study: creep test – timber specimens

Dynamic measurement of Young's modulus prior to creep test



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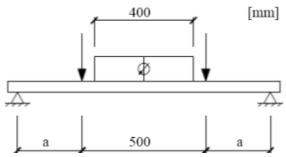
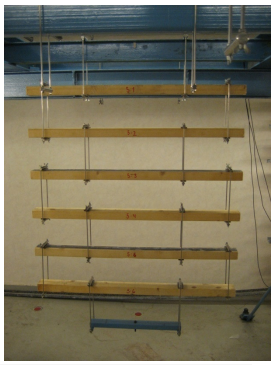
Strengthening for long-term performance

Second study: creep test – timber specimens





Creep test – loading set-up

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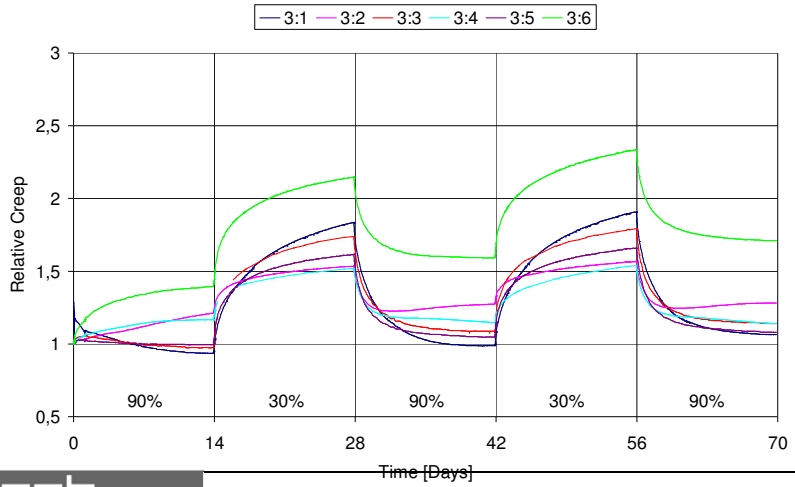
Strengthening for long-term performance

Second study: creep test – timber specimens

Relative creep – CFRP 165



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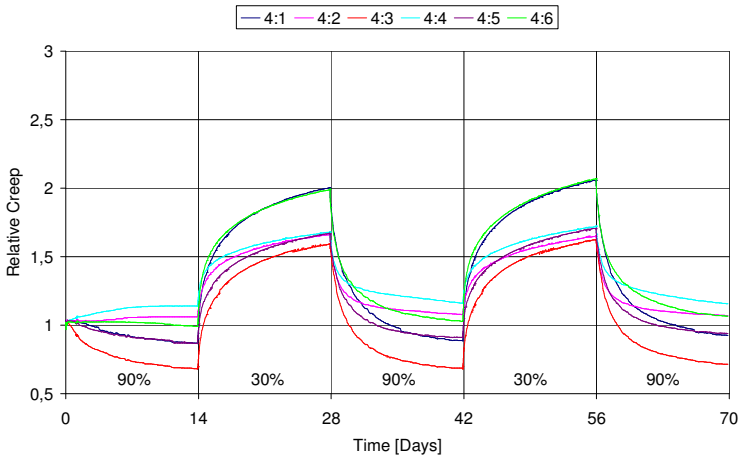
Strengthening for long-term performance

Second study: creep test – timber specimens

Relative creep – CFRP 300



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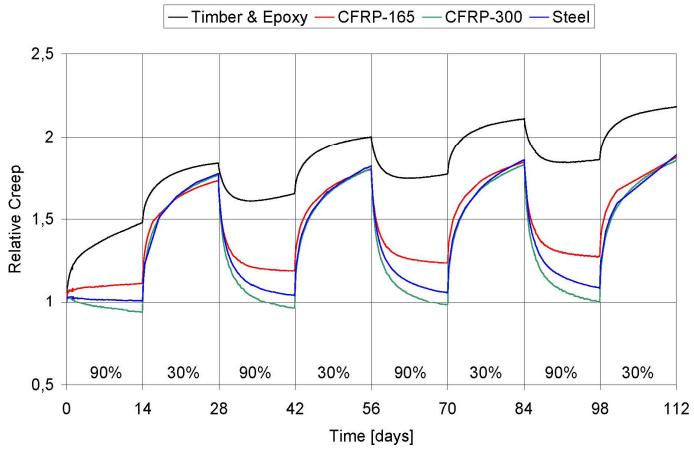
Strengthening for long-term performance

Second study: creep test – timber specimens

Relative creep – mean curves



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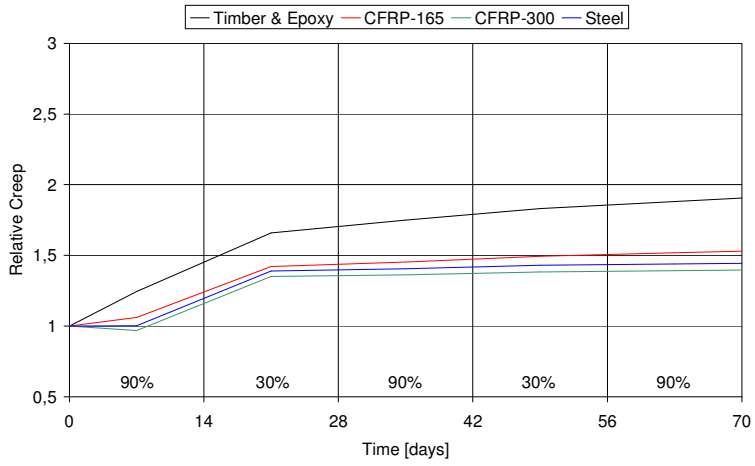
Strengthening for long-term performance

Second study: creep test – timber specimens

Relative creep, trend lines – mean curves



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Strengthening for long-term performance

Second study: creep test – timber specimens

- Stiffness of timber beams can easily be increased by applying reinforcement
- Large variation in deflection due to constrained swelling/shrinkage when reinforced on one side only
- Less creep in reinforced timber beams
- Tendency towards less mechano-sorptive creep for beams with higher initial stiffness

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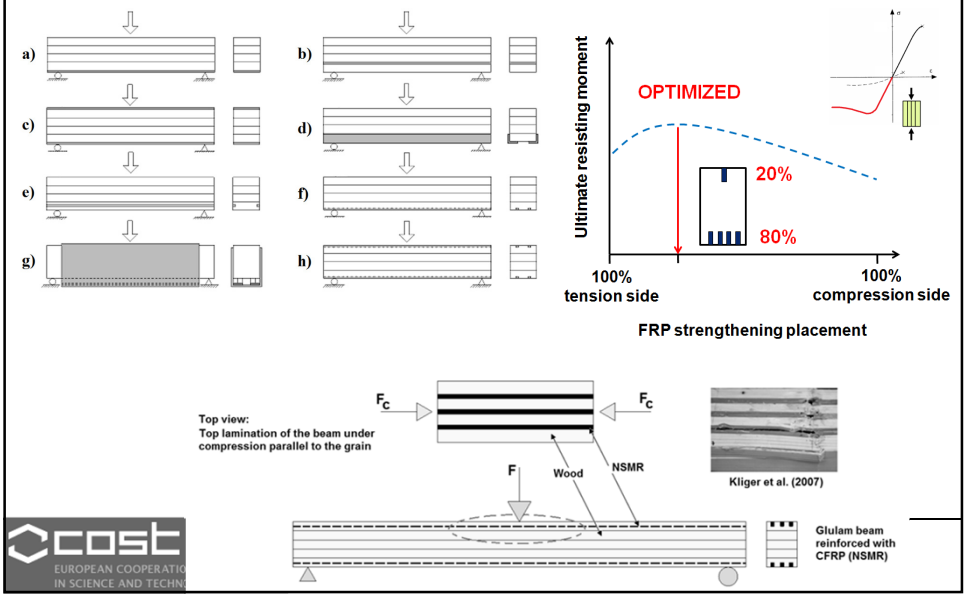
Strengthening the compression side of the beam

Third study: literature and previous knowledge



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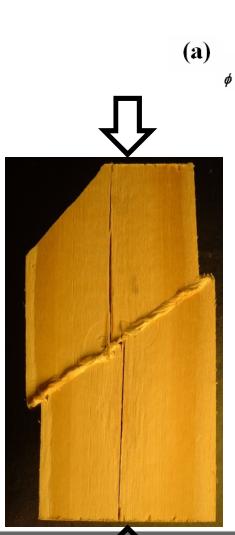
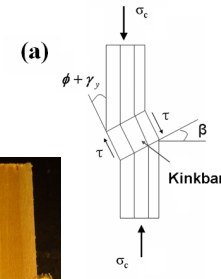
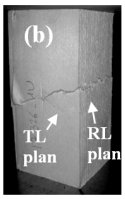
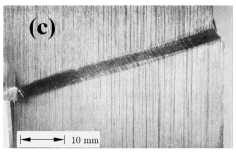
Strengthening the compression side of the beam

Third study: FRP and wood behaviour in compression

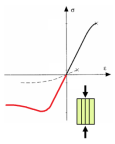


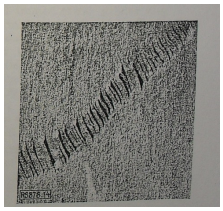


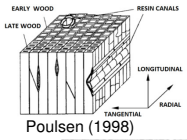




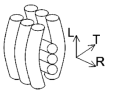
(Vogler and Kyriakides, 1999)



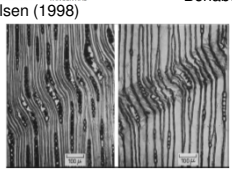




Poulsen (1998)



Benabou (2008)



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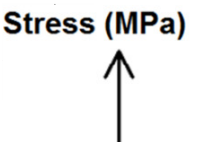
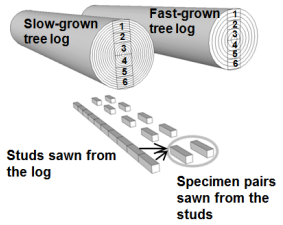
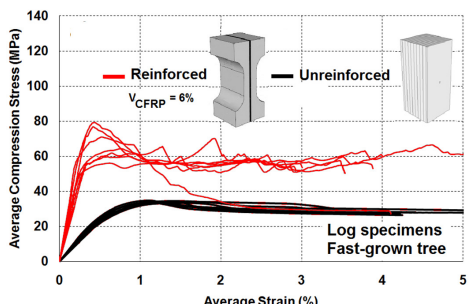
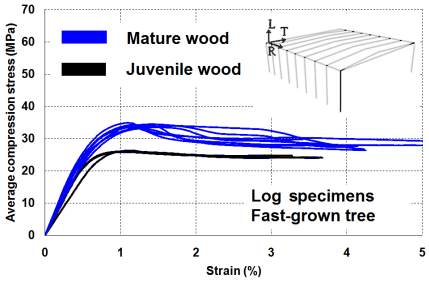


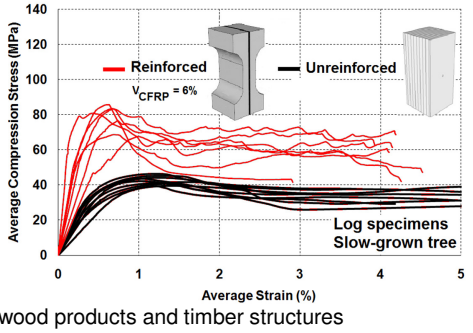
Strengthening the compression side of the beam

Third study: results





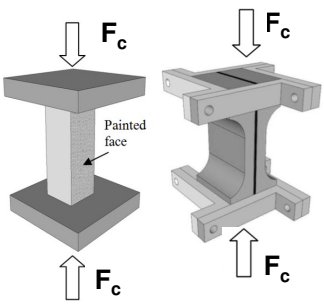


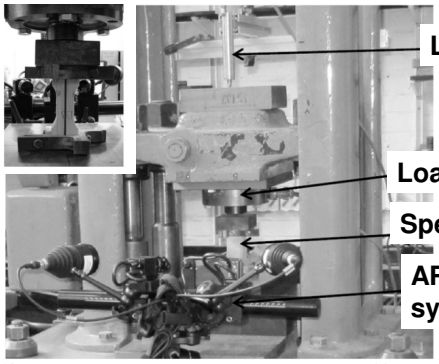


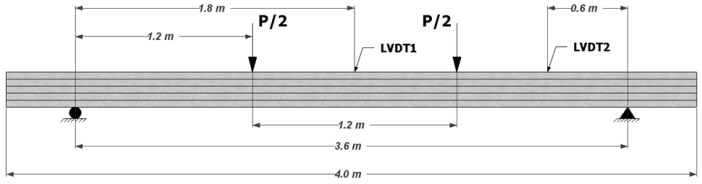
COST FP1C
engineered wood products and timber structures

Strengthening the compression side of the beam

Third study: FRP and wood - experiments







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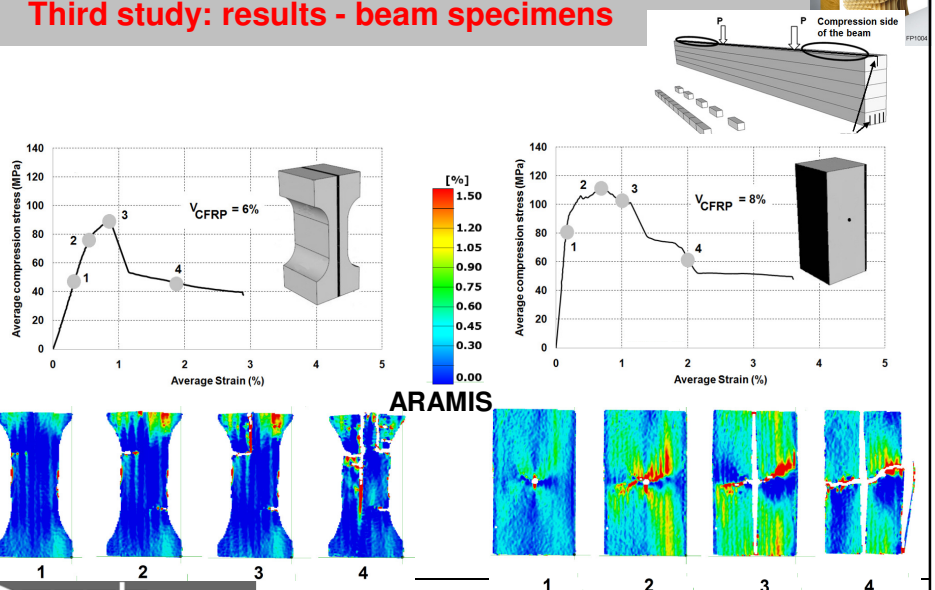
Strengthening the compression side of the beam

Third study: results - beam specimens



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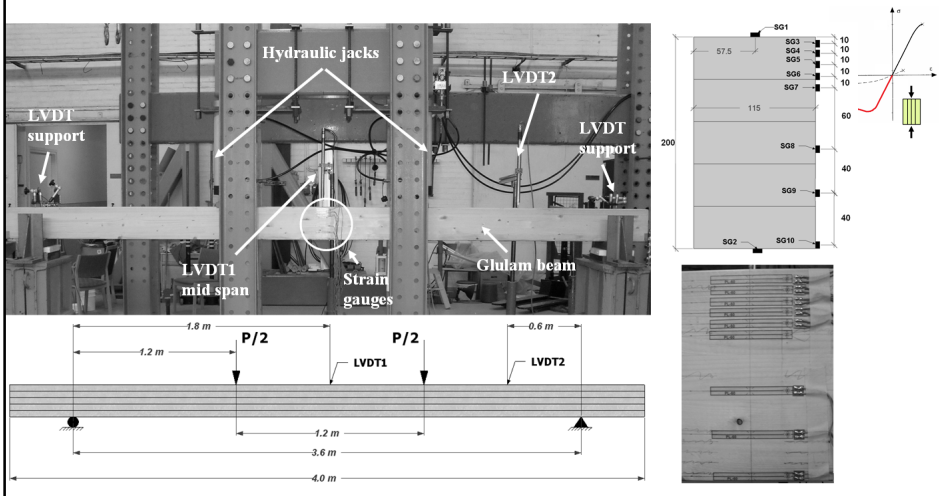
Strengthening the compression side of the beam

Third study: laboratory tests – 4-point bending test



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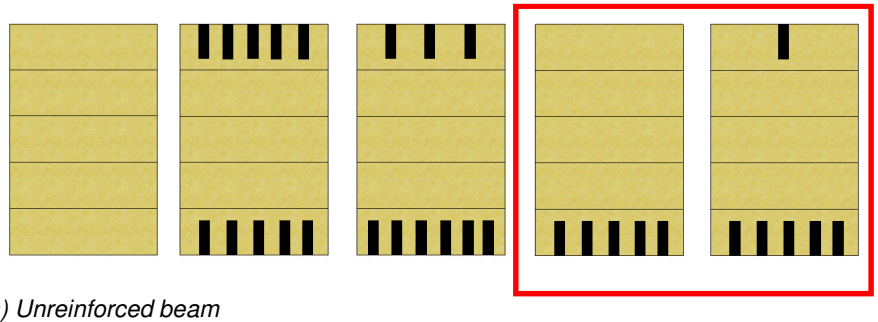
Strengthening the compression side of the beam

Third study: laboratory tests – 4-point bending test



(a) Unreinforced beam
(b) Beam with CFRP reinforcement on tension and compression side(50%-50%)
(c) Beam with CFRP reinforcement on tension and compression side (66%-33%)
(d) Beam with CFRP reinforcement on tension side only
(e) Beam with CFRP reinforcement on tension and compression side (86%-14%)

(d) = Beam 1 and (e) = Beam 2

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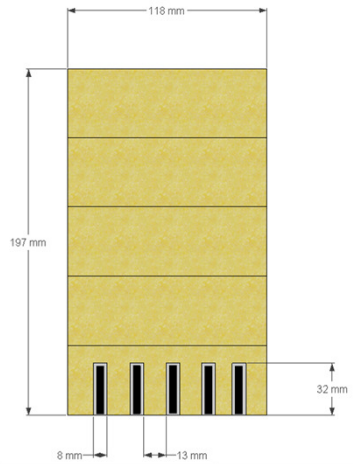
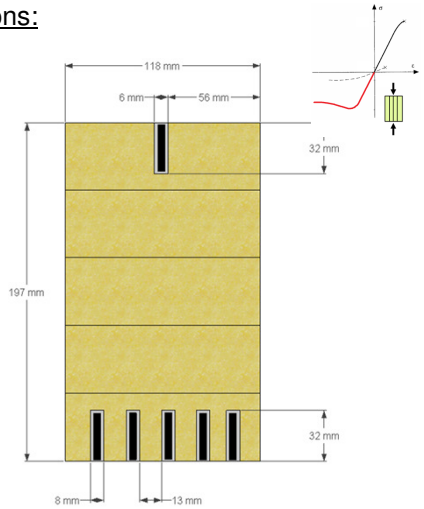
Strengthening the compression side of the beam

Third study: laboratory tests – 4-point bending test

Cross-section dimensions:





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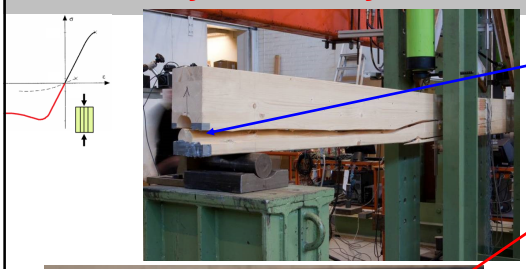
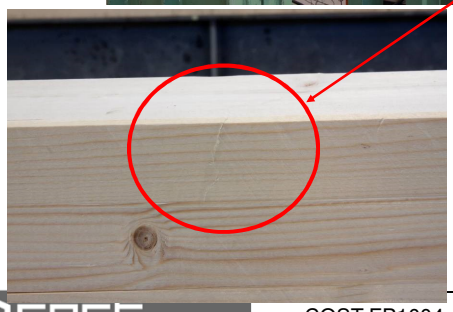
Strengthening the compression side of the beam

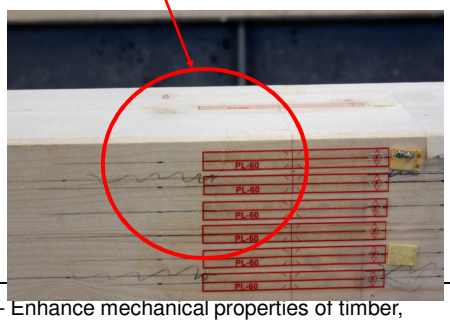
Third study: laboratory tests – 4-point bending test



Shear failure

Compression failure





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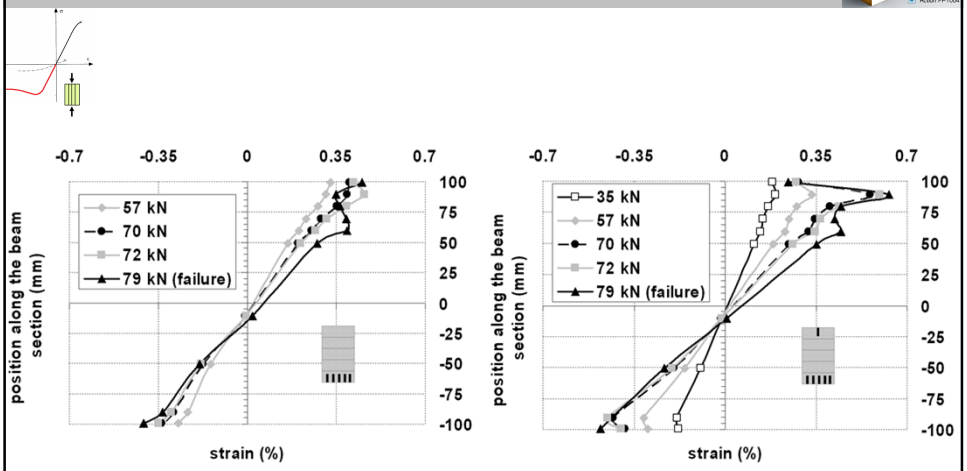
Strengthening the compression side of the beam

Third study: laboratory tests – 4-point bending test

COST FP1004 – Enhance mechanical properties of timber, engineered wood products and timber structures

Strengthening the compression side of the beam

Third study: strain along the beam depth



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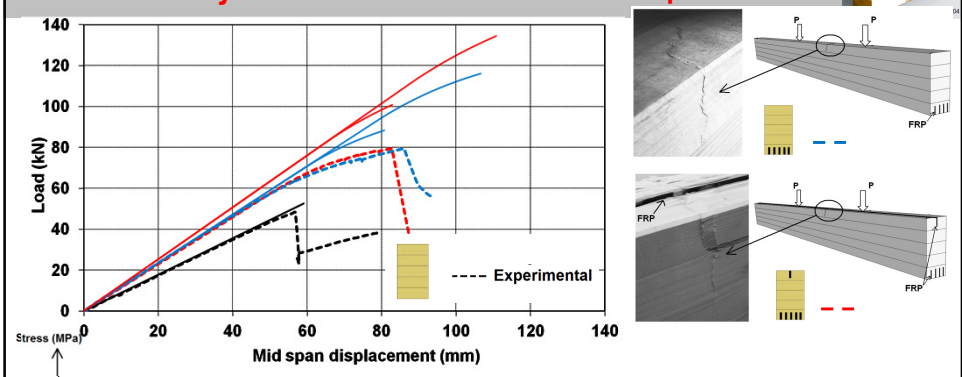
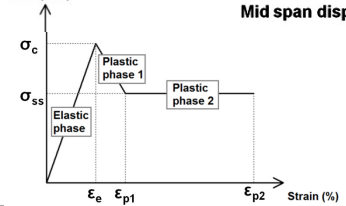
Strengthening the compression side of the beam

Third study: FRP and wood behaviour in compression





	σ_c (Mpa)		σ_{ss} (Mpa)	
	No CFRP	CFRP	No CFRP	CFRP
Experimental	62.3	67	43.3	45.4
Length effect	-22%	-22%	-22%	-22%
Mature vs. Juvenile wood	-25%	-25%	-14%	-14%

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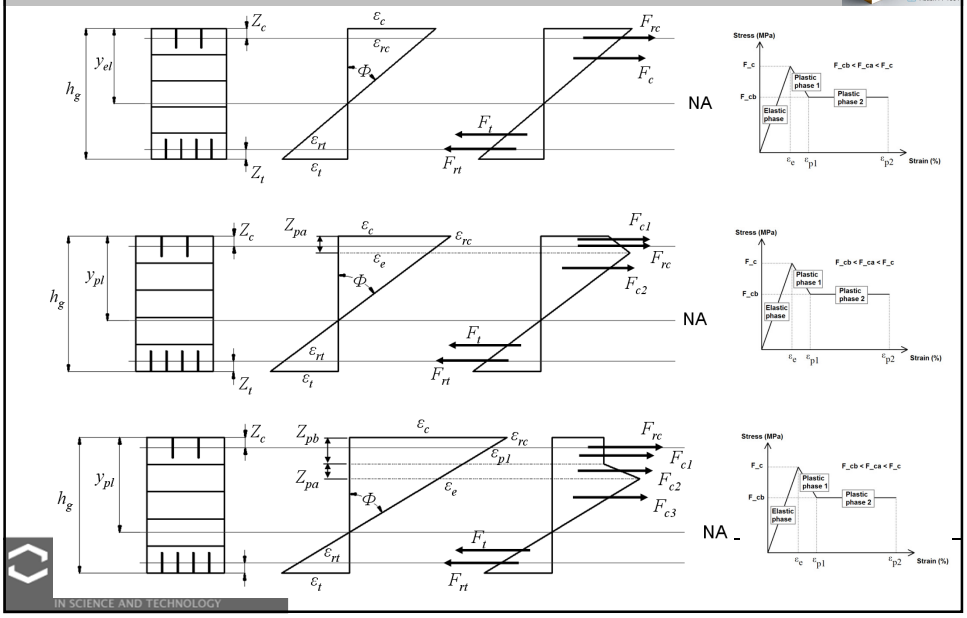
Strengthening the compression side of the beam

Third study: FRP and wood behaviour in compression

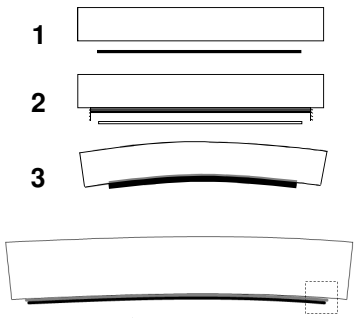


Strengthening glulam beams with pre-stressed FRP

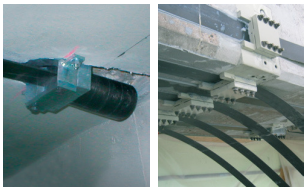
Fourth study: why do we need pre-stressing?

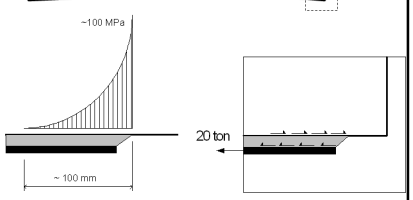
+ More efficient use of FRP materials
+ Reduction in deflection, SLS
+ Reduction in beam cross-section
+ More efficient use of materials

- High stress concentration
- Need for mechanical anchorage, when strengthening existing structures



Anchorage of FRP to (RC) concrete beams





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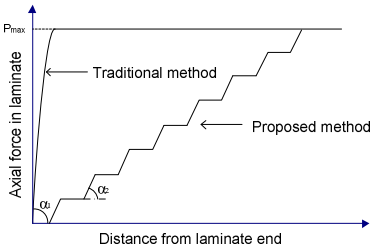
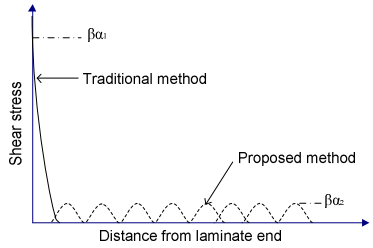
Strengthening glulam beams with pre-stressed FRP

Fourth study: pre-stressing



Method using high pre-stressing forces without the need for mechanical anchorage has been developed at Chalmers

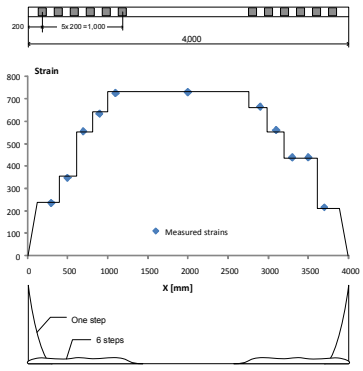


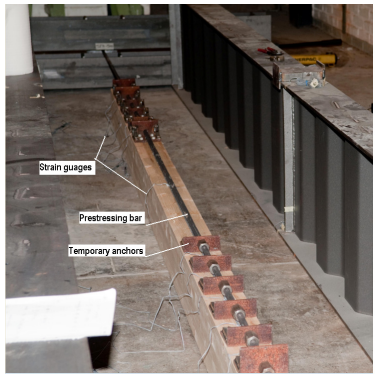
The basic concept is stepwise linking
Relationship between distribution of axial pre-stressing force and shear stress vs. distance from the laminate end according to the traditional pre-stressing method and the proposed new method

Strengthening glulam beams with pre-stressed FRP

Fourth study: pre-stressing

Axial strain profile in the laminate after releasing the pre-stressing rod

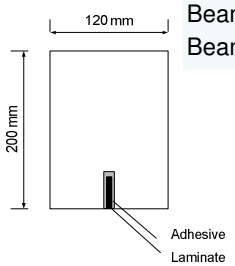




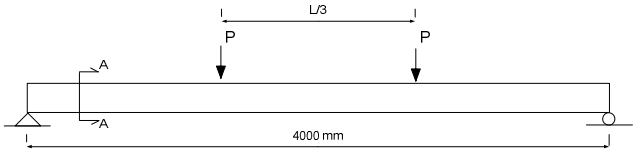
Strengthening glulam beams with pre-stressed FRP

Fourth study: pre-stressing – verification on glulam beams

Beam	Laminate dimensions [mm]	Type of laminate	Length of laminate [mm]	Pre-stressing force in the rod [kN]
Reference	-	-	-	-
Beam 1	30*2.4	S624	4000	70
Beam 2	30*1.2	S612	4000	50



Section A-A



Strengthening glulam beams with pre-stressed FRP

Fourth study: pre-stressing - results

Beam after releasing the pre-stressing force and removing the temporary posts

Beam	Failure load with pre-stressing [kN]	Failure load without pre-stressing [kN]	Increase due to strengthening without pre-stressing	Increase due to strengthening with pre-stressing
Reference	27	27	-	-
Beam 1	40	32	18%	48%
Beam 2	36	30	11%	33%

Strengthening glulam beams with pre-stressed FRP

Fourth study: pre-stressing – case study: Moelven

Multi-storey Moelven"Trä-8" – columns-beams system, **span** length **7.8 m**

Glulam beams: 165 x 630 mm, CE L40c, 14 lamellae

Bending capacity $f_{m,k}$	Tensile capacity $f_{,0,k}$	Shear capacity $f_{v,k}$	Elastic modulus $E_{0,mean}$	Shear modulus G_{mean}
30.8	25.4	2.7	13000	760

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Strengthening glulam beams with pre-stressed FRP

Fourth study: pre-stressing – case study: Moelven

Glulam beams: **165 x 630 mm**, CE L40c, **span 7.8 m, 14 lamellae**

OPTIMIZATION OF TIMBER BEAMS WITH PRESTRESSED FRP

INPUTS:

Geometry, Loads and Criterion

Initial Height:	630	mm
Initial Width:	165	mm
Span Length:	7800	mm
Self Weight, SLS:	0.42	N/mm
Permanent Load, SLS:	7.0	N/mm
Imposed Load, SLS:	4.0	N/mm
Total Load SLS:	11.5	N/mm
Total load ULS:	20.5	N/mm
Allowable instantaneous deflection (Span/?):	400	mm
Allowable Long-term deflection (Span/?):	200	mm
Height of each lamella:	45	mm

Characteristic Timber Properties

Elastic Modulus:	13000	MPa
Bending Strength:	30.8	MPa
Tensile Strength:	17.6	MPa
Compressive Strength:	25.4	MPa
Shear Strength:	3.5	MPa

Characteristic FRP Properties

Elastic Modulus:	85000	MPa
Tensile Strength:	4800	MPa
Width:	50	mm
Height:	2	mm

Run Clear All

RESULTS:

Prestressed timber with FRP

Final Height:	405	mm
Number of Lamellae:	9	
Number of Lamellae Saved:	5	
Moment Utilization Ratio:	78.1293	%
Shear Utilization Ratio:	80.1166	%
Max Instantaneous Deflection:	14.259	mm
Max Long-term Deflection:	11.4445	mm
Max Prestress:	240000	N
Analysis Type:	Plastic	

Kavan Shebli & Zachary Sheridan – 2012
Chalmers University of Technology

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Enhanced timber properties with FRP composites

Conclusions

- Glulam beams can be effectively improved with FRP composites when it comes to ductility and long-term performance
- The best way is to reinforce on both tension and compression sides
- The limit for the amount of FRP is max 2% of cross-section area of the beam
- The accuracy of prediction of the compression strength is strongly related to the choice of the wood material model
- Pre-stressed FRP on the tension side is the most effective way of enhancing large glulam beams

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