COST Action FP1004

Final Meeting

15 April – 17 April 2015 – Lisbon, Portugal

Wood-based beams strengthened with FRP laminates

Improved performance with pre-stressed systems

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  - Poor performance of various beams in bending
- Suitable strengthening materials
  - FRP and resin materials
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- Pre-stressed reinforced glulam beams
  - Overview and main advantages
  - Various suitable methods

Background

- Need to strengthen existing structures
  - floors, roofs, industrial girders or timber bridges
- Newly designed timber structures could be more price competitive
  - if the height of the structural members was minimised
  - beams and floor systems (in multi-storey buildings) and timber bridges

Background

- The design of simply supported glulam beams is often governed by SLS design criteria such as
  - the final deflection criterion or vibrations,
  - both governed by stiffness
- Old structures may deteriorate or need to carry additional loads
  - Strengthening in both ULS and SLS is needed

Introduction

Background

The reinforcement of timber structures using steel has been practised for over 60 years.

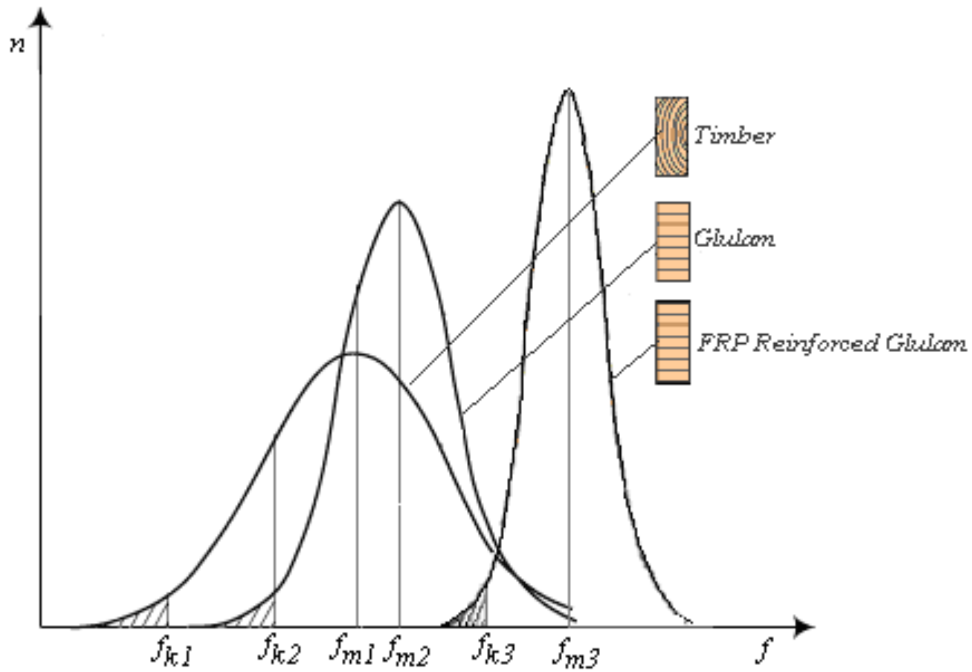
The incompatibility problem between wood and steel:

- the difference in hygro-expansion and creep properties can result in failure in the glue line.

Development of Fibre Reinforced Polymers (FRP) and suitable adhesives offers new opportunities!

Using FRP offers:

- Increased stiffness
- Lower variability
- Higher ductility



Ref: André 2011

Aims

- to summarise the advance in wood-based flexural members strengthened with FRP laminates including:
  - slack systems
  - pre-stressed systems
- to show recent developments to avoid the need to anchor pre-stressed laminates at the end of a beam
  - improved performance of such a system

Suitable strengthening materials

FRP materials – fibre properties

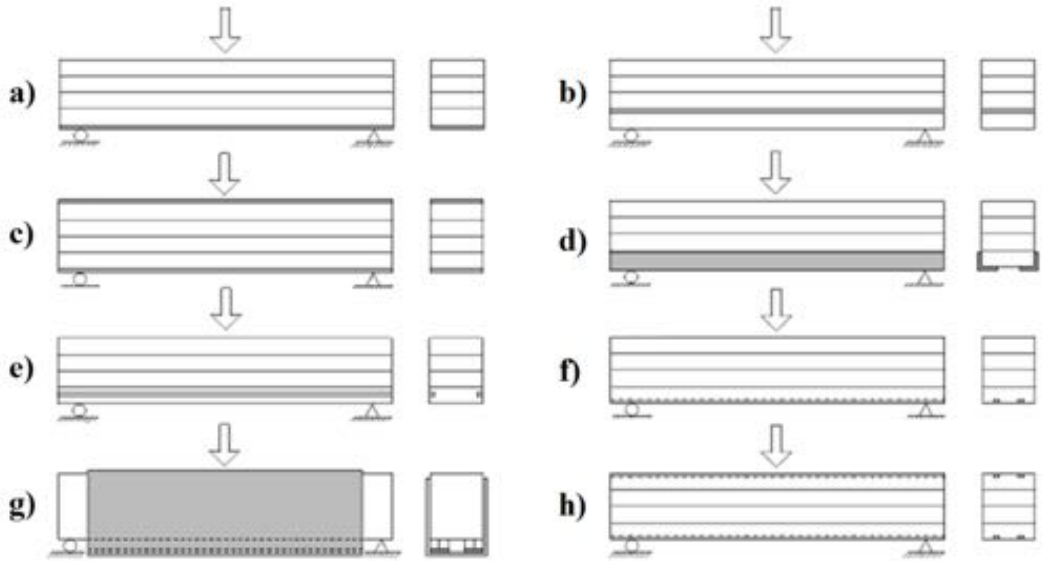
	Axial E–modulus [GPa]	Tensile strength [GPa]	Poisson's ratio	Density ρ [Mg/m³]
E-glass fibres	76	2.0	0.22	2.6
HM carbon fibres	380	2.4	0.2	1.95
HS carbon fibres	230	3.4	0.2	1.75
Aramid fibres	130	3.0	0.35	1.45
Basalt fibres	89	2.5 – 4	0.3	2.75

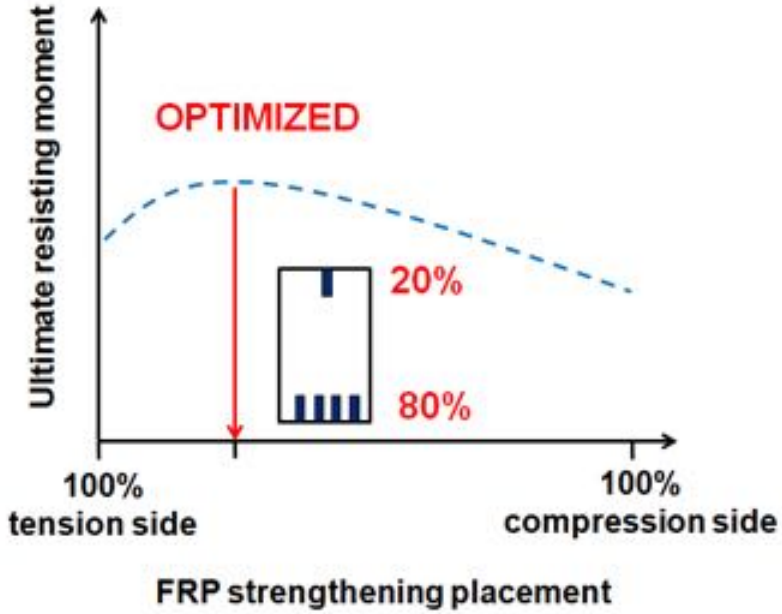
Ref: Hull and Clyne (1996) and net composites (2011)

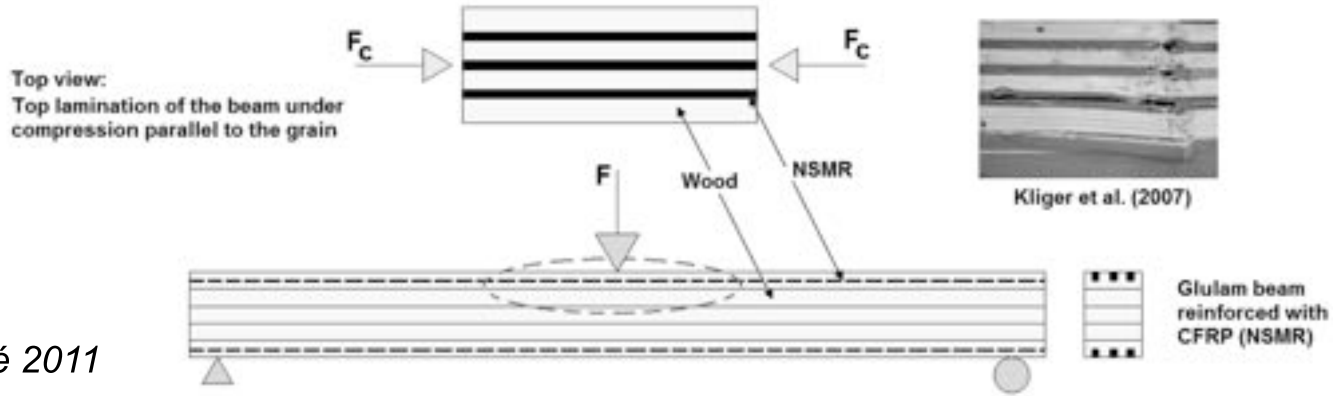
Epoxy resins (E-modulus 2-5 GPa) are the most common ones used together with CF to produce CFRP.

Reinforcing timber beams by slack reinforcement

Literature review



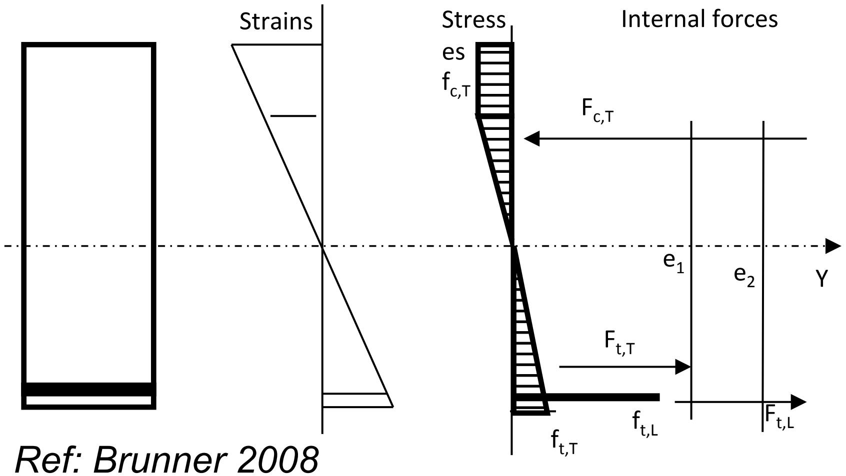




Ref: A André 2011

Reinforcing timber beams by slack reinforcement
Design models

Elastic-plastic design calculation model



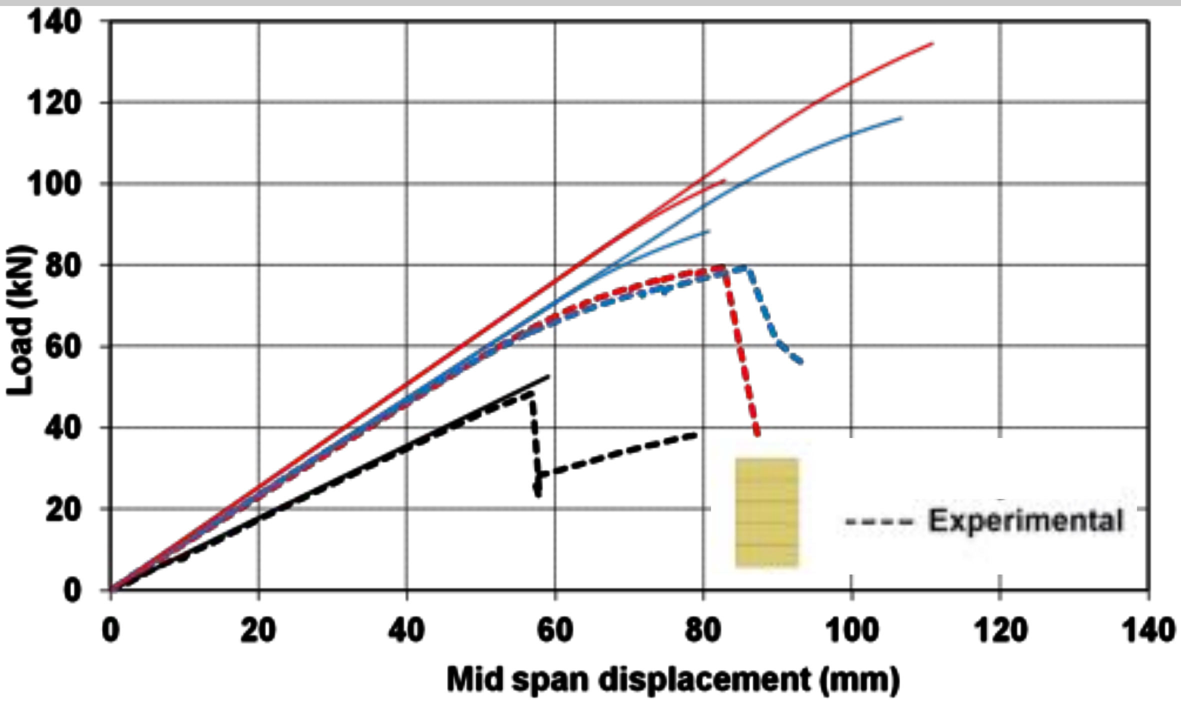
Ref: Brunner 2008

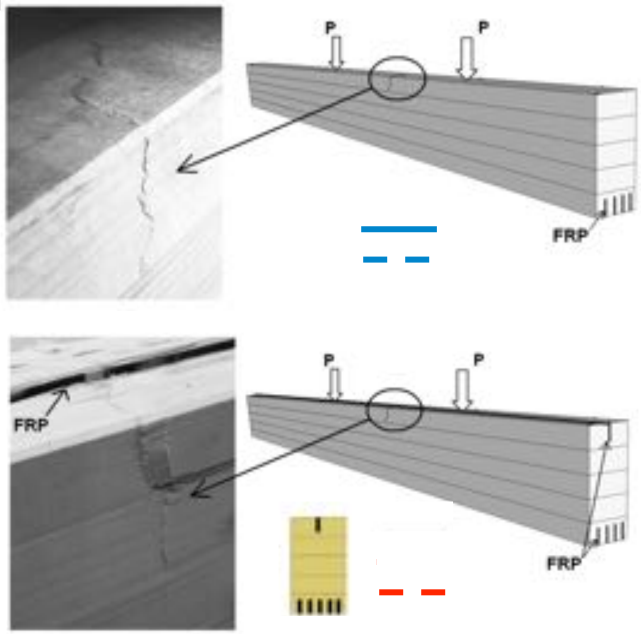
Assumptions:
- full interaction
- FRP is linear elastic until failure
- no de-bonding

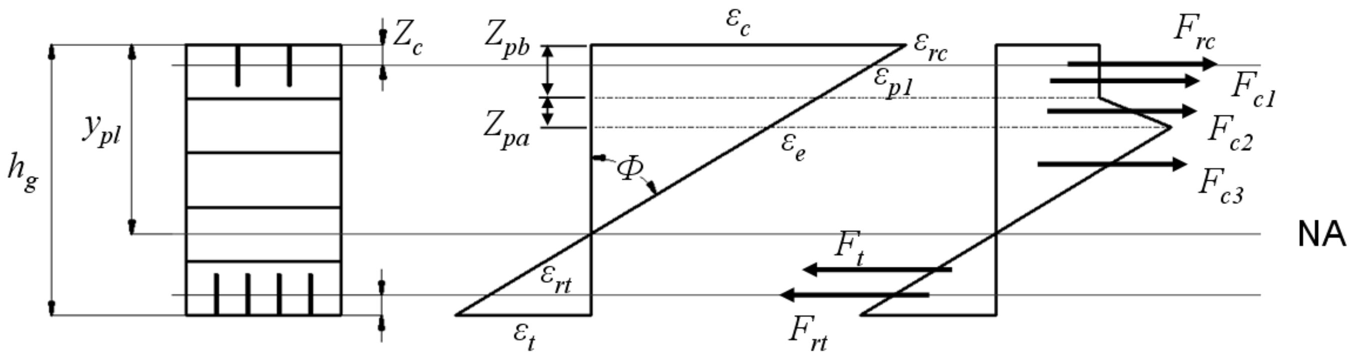
ULS – to determine the ultimate moment capacity
SLS – to determine deflection

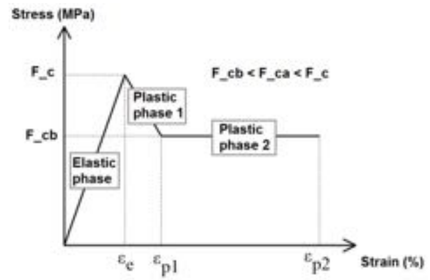
Reinforcing timber beams by slack reinforcement

Strengthening on the compression side









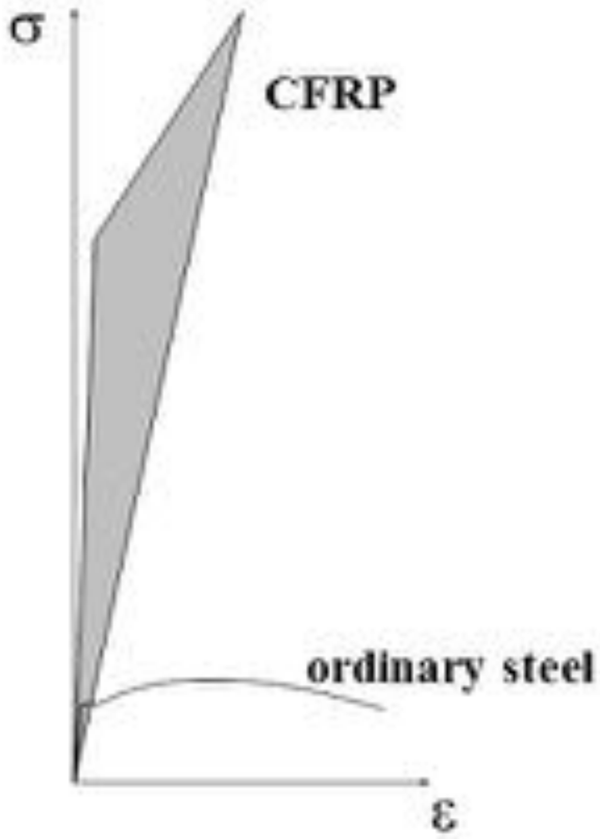
COST FP1004 – Enhance mechanical properties of timber, engineered wood products and timber structures

Reinforcing timber beams by slack reinforcement
Conclusions

CFRP is much stronger than steel, concrete, **timber etc.**

CFRP is also stiffer than steel and all FRPs are much stiffer than timber

But…. CFRP is not utilised as slack or passive reinforcement**!**



Why pre-stressing?

General advantages of pre-stressing any FRP systems over non-pre-stressed systems are:

- Need for less FRP strengthening material
  - FRP utilised to 100% – much more cost efficient!
- Increase in load-bearing capacity
- Significant improvement when it comes to the design in SLS
- Increase in shear capacity via the compressive stresses induced in the beam

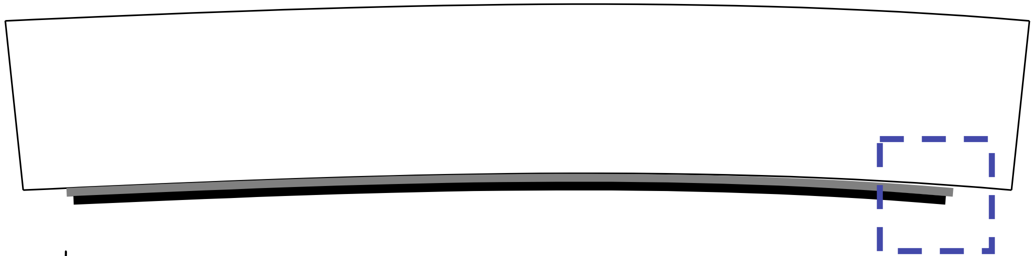
Pre-stressed reinforced glulam beams

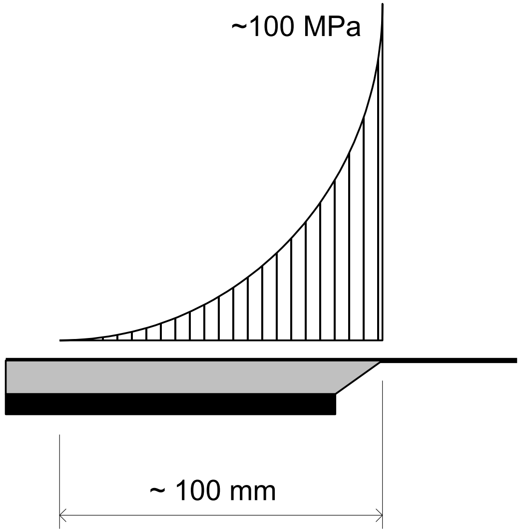
Why pre-stressing?

- The eccentric pre-stressing on the tension side of a beam induces significant compressive stresses, which opposes the tensile stresses due to the external loads
- In design, the pre-stressing force is considered as an axial compressive force
- Until now **the pre-stressing systems were not successfully applied to timber** mostly due to the de-bonding of the FRP laminate as a result of concentrated shear and peeling stresses at the laminate end

Pre-stressed reinforced glulam beams

Challenge





Typical strength of adhesive is 25 MPa

Timber strength is about 1 - 3 MPa

↓

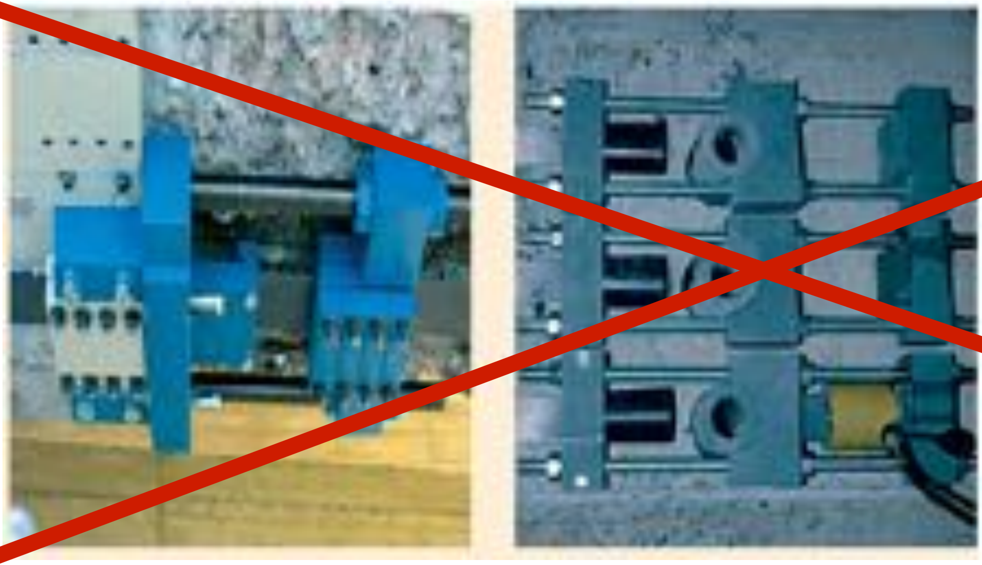
Factor 100!

How to apply the pre-stress force?
How to transmit the force between FRP and timber elements?

Pre-stressed reinforced glulam beams

Challenge

The concrete industry solved this problem with various mechanical anchoring devices



but….

- tedious preparation (drilling, etc..)
- maintenance and durability issues
- and need for inspections

- aesthetics

Methods of pre-stressing based on literature

Various methods to avoid anchoring devices:

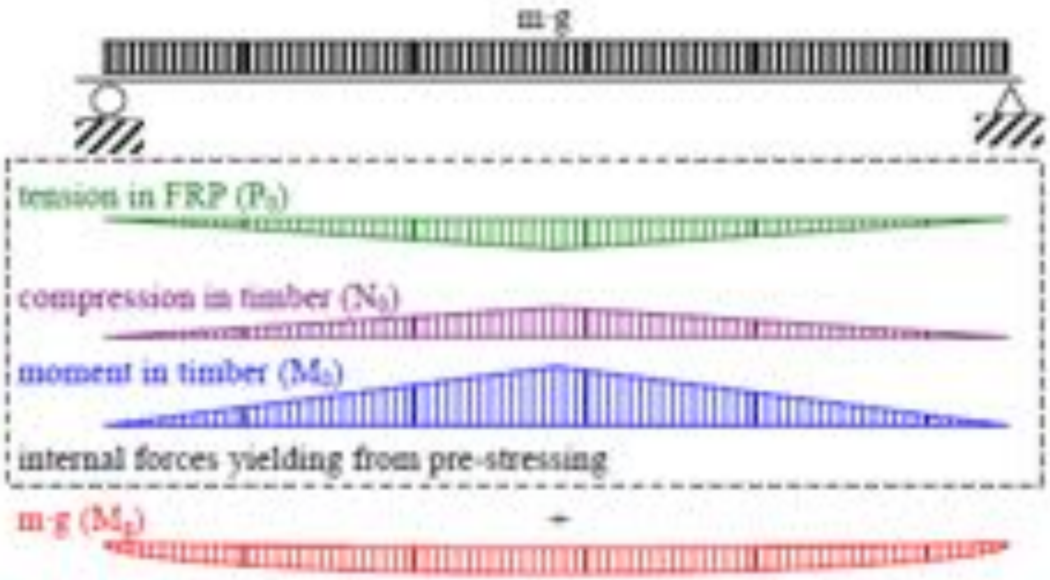
1. Pre-cambering of timber before installing FRP
2. Releasing the pre-tensioning force while the bond line is wet
3. Gradient pre-stressing by curing the epoxy from the middle of the beam
4. Step-wise pre-stressing method

Methods of pre-stressing based on literature

Method for pre-cambering timber before installing FRP

- *Lehmann et al. (2006)*

- Pre-cambering is achieved using an adjustable prop located at the centre of the beam.
- A triangular bending moment distribution in the beam due to the prop force and a low constant shear stress in the glue line are achieved.



Methods of pre-stressing based on literature

Method for pre-cambering timber before installing FRP

\- *Lehmann et al. (2006)*

- The desired pre-cambering of the beams during production was achieved with the testing machine. The curing of the adhesive was done at elevated temperatures to 90°C.

Increase in the load-bearing capacity in bending was ~ 30% and contribution of the strengthening in SLS was ~ 40%.

Method of releasing the pre-tensioning force while the bond line is wet - *Dagher et al. (2010)*

- Pre-stressing force 98 kN was applied to GFRP (1% of the cross-section) on the steel supports
- PRF adhesive was applied to the GFRP after pre-tensioning The glulam beam was then placed on top of the GFRP and twenty-four clamps were placed along the beam
- An average clamping pressure of 1.0 MPa was applied.

Pre-stressed reinforced glulam beams

Methods of pre-stressing based on literature

Method of releasing the pre-tensioning force while the bond line is wet - *Dagher et al. (2010)*

- After clamping, but before the adhesive began to cure, the pre-tensioning jack forces were released
- After the adhesive cured, the GFRP laminate was cut and the clamps were released

Glulam beams (6.7 m long) showed 95% and 38% higher strength for pre-stressed and for non-pre-stressed beams respectively, with the same GFRP

Methods of pre-stressing based on literature

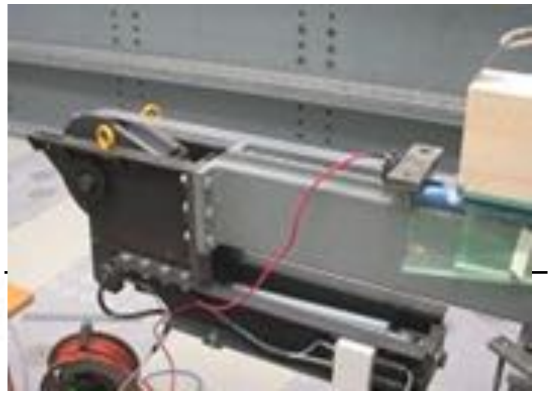
Method of gradient pre-stressing by curing the epoxy from the middle of the beam (EMPA) - *Stöcklin & Meier (2003)*

- Gradual anchoring is achieved by first bonding a fully pre-tensioned section in the middle of the FRP strip at mid-span,
- The pre-stressing force is slightly reduced and another section is bonded on each side of the laminate using the electric heating system,
- This process is repeated in several stages until the entire length of the strip is bonded and the pre-stressed level at the ends of the strips has been reduced to a low level.

Brunner (2008) used this device to strengthen glulam beams with pre-stressed FRP laminates

(a)

(b)



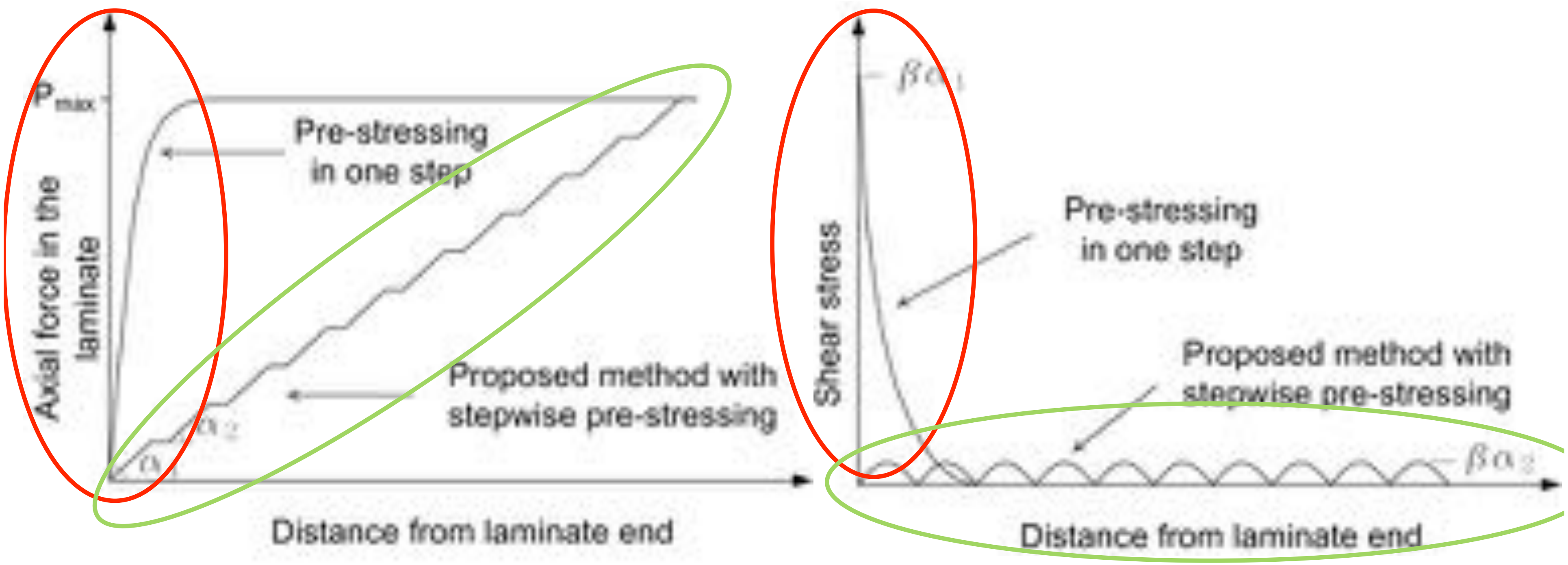
Methods of pre-stressing based on literature

A drawback to the presented method:

- The first two methods are not suitable for *in-situ* applications
- EMPA method
  - long time needed to complete each step of pre-stressing
  - precision involved in releasing the pre-stressing force
  - limits the total practical number of steps and, as a result, maximum pre-stressing force

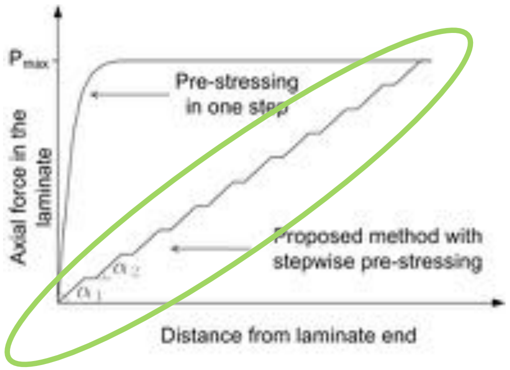
Pre-stressed reinforced glulam beams

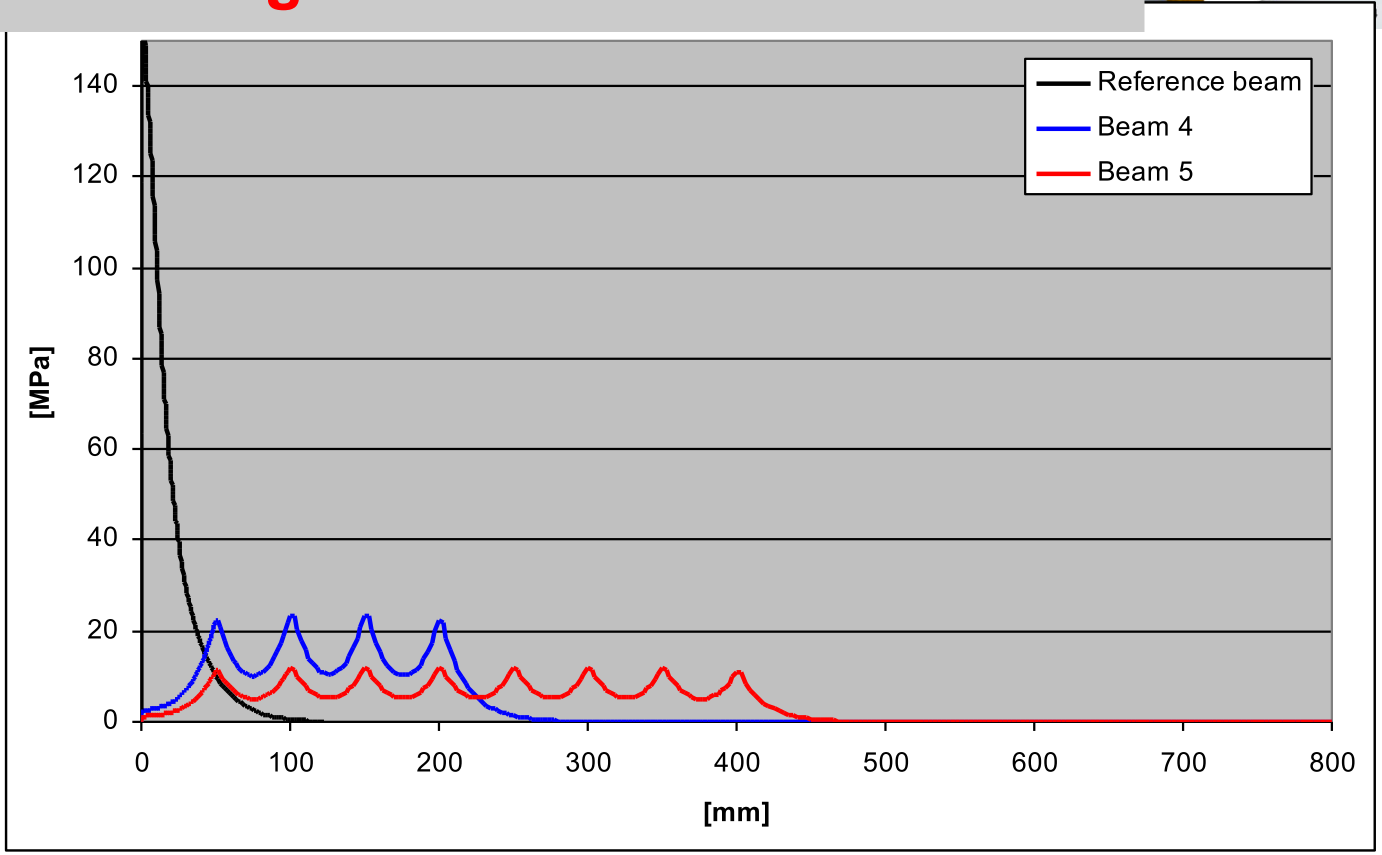
Step-wise pre-stressing method



Pre-stressed reinforced glulam beams

Step-wise pre-stressing method





The slope could be controlled by increasing the number of steps so that the interfacial stresses in the bond line are well below the strength of the adhesive or the substrate material.

Pre-stressed reinforced glulam beams

Step-wise pre-stressing method

Applying the pre-stressing step-wise can be performed in two ways:

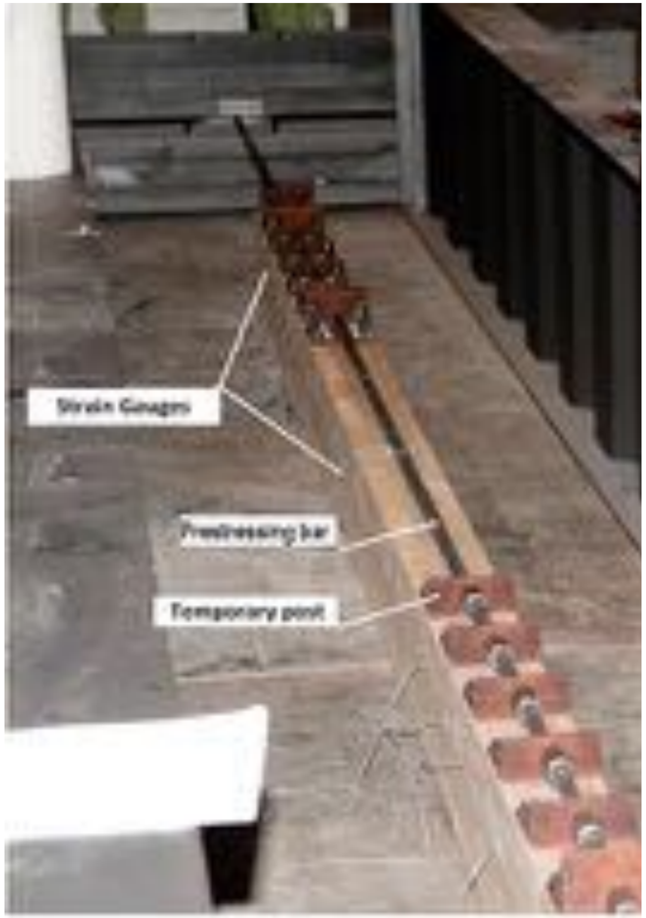
•bonding the laminate in the non-pre-stressed state and eventually releasing the force in the beam

•using a special device developed at Chalmers University of Technology

The first prototype was tested on two glulam beams and the force was applied in six steps.

Step-wise pre-stressing method

A prototype was tested on two glulam beams



Temporary posts were used to pre-stress the beam in six steps.
Two beams (120 mm x 200, GL30h) were pre-stressed with near-surface-mounted CFRP laminates

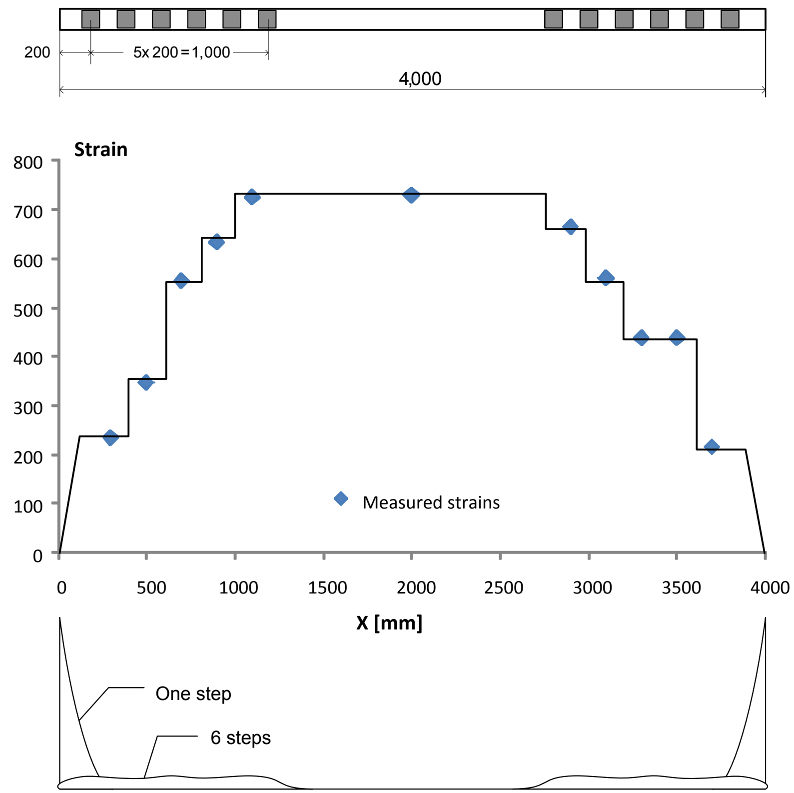
Beam 1: pre-stressing force of 70 kN
STO laminate 30 mm x 2.4 mm
Beam 2: pre-stressing force of 50 kN
Sika laminate 30 mm x 1.2 mm

Pre-stressed reinforced glulam beams

Step-wise pre-stressing method

A prototype was tested on two glulam beams

The resulting profile of the axial strains in the laminate in the second beam



Near-surface-mounted
Prior to mounting the posts, the laminate was placed in a premade groove filled with epoxy adhesive.

The total pre-stressing force was applied to a pre-stressing bar passing through temporary posts mounted on the beams

After curing the adhesive, the force in the bar was released.

Step-wise pre-stressing method

A prototype was tested on two glulam beams – test results

The two beams plus an unstrengthened beam (reference) with the same dimensions were loaded to failure using 4-point bending

The increase in strength in relation to the unstrengthened beam was 18% (for F=70 kN) and 11% (for F=50 kN) respectively.

The increase in stiffness was 48% (for F=70 kN) and 33% (for F=50 kN) respectively.

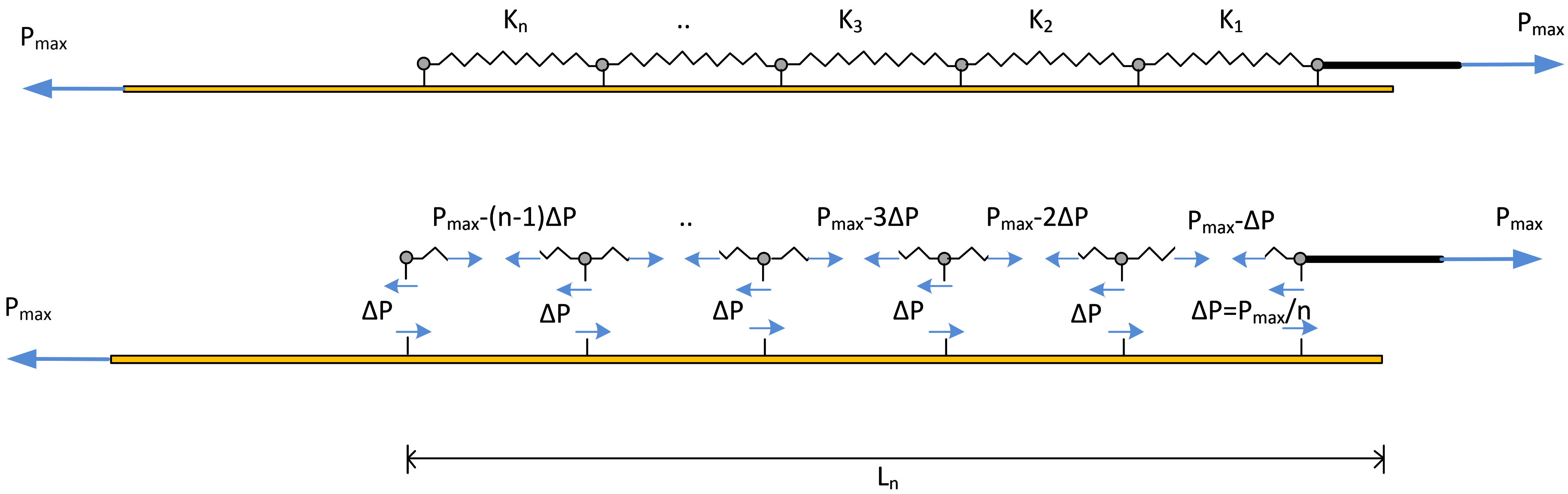
The amount of the pre-stressing force transferred to the laminate using this solution is fairly limited, i.e. less than 10% of the pre-stressing force in the bars is transferred to CFRP

Pre-stressed reinforced glulam beams

Step-wise pre-stressing method

A more effective method is needed
if the pre-stressing force is directly applied to the laminate

The idea is to control the magnitude of the interfacial stresses by manipulating the pre-stressing force profile in the laminate

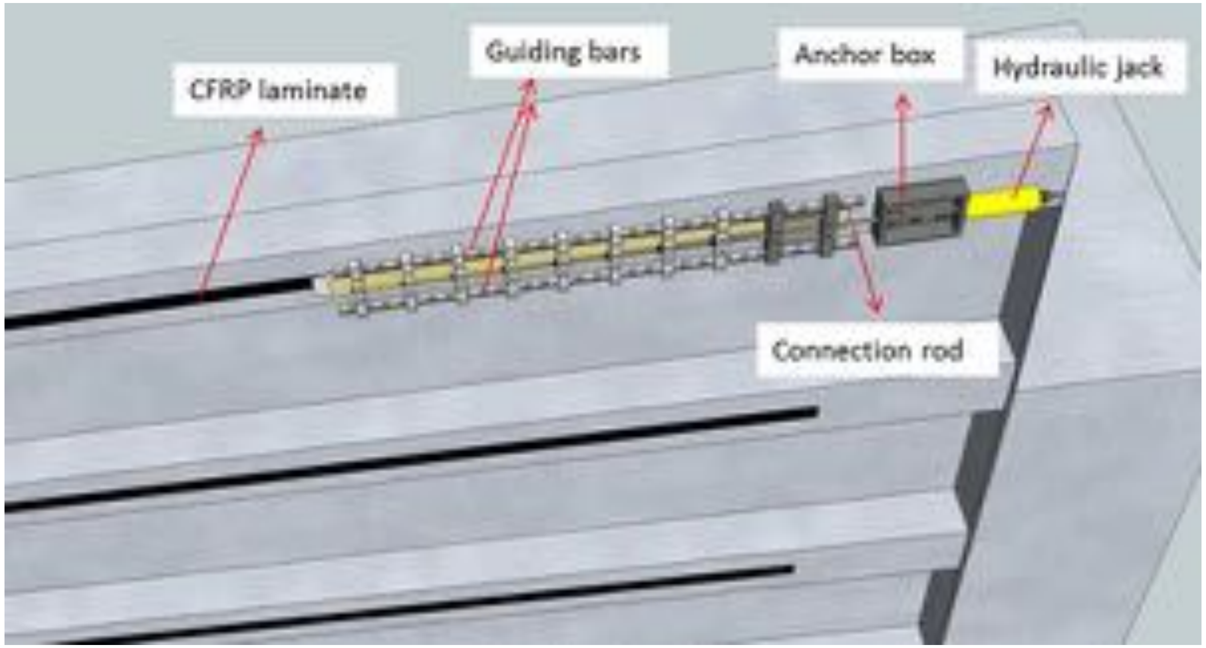


The pre-stressing force is gradually built up in the laminate instead of pre-stressing to the maximum level and then releasing the force.

Pre-stressed reinforced glulam beams

Step-wise pre-stressing method

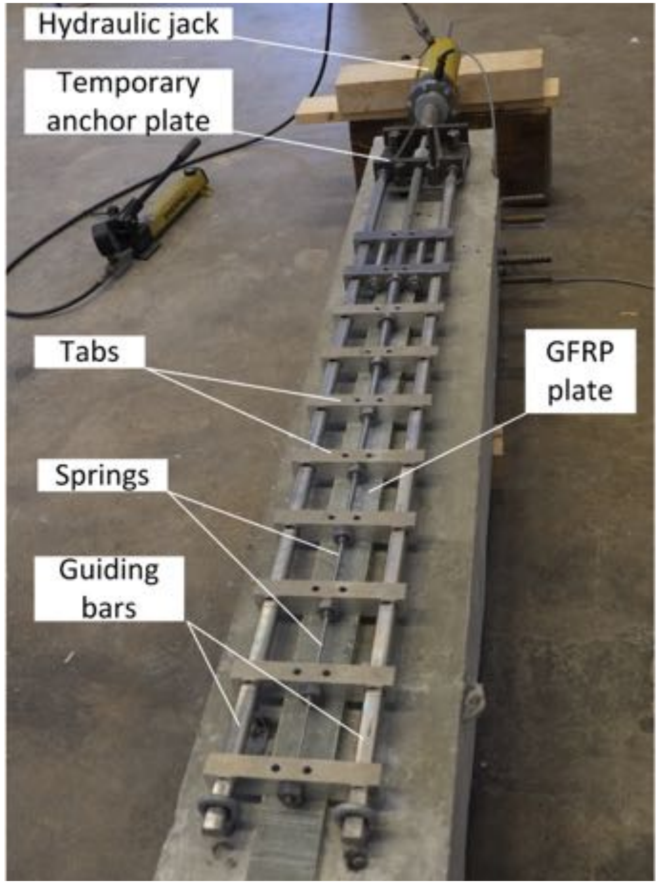
Mounting the pre-stressing device on the structure using a temporary anchor box and guiding rails



The difference between this method and the one developed at EMPA is that the variable pre-stressing force profile will be delivered to the laminate at once

Pre-stressed reinforced glulam beams

Step-wise pre-stressing method



The pre-stressing device has been successfully used to install pre-stressed laminates with forces up to 150 kN (10 steps) on concrete beams.

It is easy to apply to timber or glulam beams specifically *in situ* on existing structures.

*The device is patented by Tenroc Technologies AB (*www.tenroc.se*)*

Pre-stressed reinforced glulam beams

Conclusions and advantages

ULS – often passive or slack reinforcement is sufficient!
but, compared with pre-stressed FRP systems, more FRP material is required to reach the same level of strengthening

SLS – governs the majority of beams
the simple way to construct new beams is to pre-camber, but, for certain projects, when the building height plays an important role – minimising the height of a beam can be an option – pre-stressing!

When a beam needs to be strengthened on site, the stepwise pre-stressing method, developed at Chalmers, offers a good and simple solution.

Conclusions and advantages

The method is even more cost efficient in existing structures if there is no need for permanent anchors at the end of the laminate.

It is also more efficient, as the FRP material can be utilised up to 100%.

For new construction, it is possible to reduce the height of glulam by almost 25% while still fulfilling the same design requirements.

Pre-stressed reinforced glulam beams


Thank you for your attention!