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ORIGINAL

Wood-based beams strengthened with FRP laminates: improved performance with pre-stressed systems

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Abstract Using bonded fibre-reinforced polymer (FRP) laminates for strengthening wooden structural members has been shown to be an effective and economical method. In this paper, properties of suitable FRP materials, adhesives and two ways of strengthening beams exposed to bending moment are presented. Passive or slack reinforcement is one way of strengthening. The most effective way of such a strengthening was to place reinforcement laminates on both tension and compression side of the beam. However, the FRP material is only partially utilised. The second way is to apply pre-stressing in FRP materials prior to bonding to tension side of flexural members and this way was shown to provide the most effective utilisation of these materials. The state of the art of such a strengthening and various methods are discussed. Increasing the load-bearing capacity, introducing a pre-cambering effect and thus improving serviceability which often governs the design and reducing the amount of FRP reinforcement needed are some of the main advantages. A recent development on how to avoid the requirement for anchoring the laminates at the end of the beams to avoid premature debonding is shown, and the advantage of such a system is described.

1 Introduction

Wood-based beams, such as solid structural timber, glued-laminated timber (glulam) or other engineering wood products (EWP) might need strengthening in existing structures such as floors, roofs, industrial girders or even timber bridges for several reasons such as increase in service loads or degradation of the material. Sometimes newly designed timber structures could be more price-competitive if the height of the structural members was minimised. Examples of such members are column and beam systems (in multi-storey buildings) and timber bridges where the total construction height of beams and deck can be of significant importance.

The design of simply supported glulam beams is often governed by serviceability limit state (SLS) design criteria such as the final deflection criterion or vibrations, both governed by stiffness. The natural defects, present in timber, are the source of large variations in mechanical properties. This drawback could be partially counteracted by using EWP instead of solid wood. However, substantial improvements in stiffness are very difficult to achieve for all types of wood-based products. By gluing timber into products such as glulam, variability is to some extent reduced by including several different timber pieces and their redistribution.

Further reduction in variability in mechanical properties can be achieved by adding more standardised artificial materials such as fibre reinforced polymer (FRP) materials, obtaining less variability while improving structural performance of the timber elements.

Four decades ago, FRP composite materials made their entrance in the civil engineering arena. FRP materials have very high specific strength and stiffness, very good durability and fatigue performance and are very light

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weight. Due to advantages offered by composite materials and adhesive bonding, FRP bonding is generally used as an alternative strengthening or repair technique for traditional upgrading methods. The large difference in modulus of elasticity of timber and FRP composites (more specifically carbon FRP) makes it ideal for strengthening timber elements, since at already small deformations the FRP material is activated as a load bearing agent and contributes to stiffness and ultimate strength of the member. Therefore, adding a small amount of very stiff FRP material to wood-based products improves the total stiffness of the composite wood-based member which is mainly due to the large difference between the modulus of elasticity of the wood and FRP composite material. The reinforcement of timber structures has been practiced for over 50 years. Early attempts were made by, for example, Granholm (1954) using steel rods placed in grooves in the top and bottom surface of timber beams. Since then, a large number of studies was carried out on using steel reinforcement for strengthening of timber beams, see for example Wandgaard (1964), Biblis (1965) and Krueger (1973). However, one problem when using steel as reinforcement is the incompatibility between wood and steel. Most notable, the difference in hygro-expansion and creep properties can result in failure in the glue line between the wood and steel.

A possible solution for avoiding these problems is to use FRP composite laminates. Attempts for using FRP as a strengthening material for wood were reported in the 1990s (Van de Kuilen 1991; Plevris and Triantafillou 1992; Dagher et al. 1996; Tingley 1996). The flexural strengthening method by gluing FRP laminates on the tension side of a beam is the most straightforward and has been used during the past few decades.

In order to obtain a large contribution of FRP strengthening in load bearing capacity, a large transfer of force to FRP laminate is necessary. Study of the force transfer mechanism in adhesive joints shows that a large portion of the force is normally transferred at a rather short distance at the ends of the laminate referred to as anchorage length. The larger the difference between the modulus of elasticity of timber and FRP material, the higher the force carried by the FRP laminate which leads to higher shear stresses along the anchorage length in the adhesive layer and the wooden substrate. Due to the limited shear strength of wood and tension perpendicular to the grain, the failure of FRP bonded timber members is usually governed by debonding of the FRP laminate at timber material level. Proper selection and application of the adhesive will ensure that debonding due to cohesion or adhesion failure does not occur. Debonding reduces the utilisation of the composite laminate and is usually characterised by sudden separation of the strengthening laminate from the structural member. This is an unfavourable failure mode since debonding usually takes place way before the FRP laminate reaches its ultimate strength. The mechanics of bond-line delamination is discussed in Schober et al. (2015). This phenomenon dramatically reduces the efficiency of the strengthening. A substantial amount of research has been devoted to finding possible solutions to increase the efficiency of FRP bonded strengthening systems.

A solution to exploit the full capacity of the FRP laminate is to use pre-stressing in the composite material before bonding to the structural member. This solution has been the subject of several studies since the 1990s, see for example (Triantafillou and Deskovic 1992; Wight et al. 2001; Pellegrino and Modena 2009; Motavalli et al. 2011). The idea is to induce a pre-stressing force which enables the composite laminate to reach its ultimate strength. Applying pre-stressing in FRP materials prior to bonding to tension side of flexural members offers the most effective utilisation of these materials. Increasing the load-bearing capacity, introducing a pre-cambering effect and thus improving serviceability which often governs the design and reducing the amount of needed FRP reinforcement are some of the advantages (Rodd and Pope 2003; Lehmann et al. 2006; Brunner and Schnueriger 2007; Brady and Harte 2008; Dagher et al. 2010). The shear capacity of timber beams could also be improved via the induced compressive stresses due to pre-stressing (Kliger and André 2013).

A major problem with using pre-stressed CFRP laminates is the tendency of the strengthening laminate to debond at already very low pre-stressing levels. Therefore, a general requirement when it comes to using pre-stressed FRP laminates is the need for the anchorage of the composite laminate at the end. However, most recently, there have been attempts to develop new methods where anchoring the end of laminates can be avoided (Dagher et al. 2010; Lehmann et al. 2006; Brunner and Schneuriger 2007; Haghani and Al-Emrani 2014).

The main aim of this paper is to summarise the advance in wood-based flexural members strengthened with FRP laminates including pre-stressed systems. A recent development on how to avoid the requirement for anchoring the laminates at the end of the beams is shown and the advantages of such a system are described.

2 Suitable strengthening materials

The most common FRP materials used to strengthen wood-based beams are those made of glass and carbon fibres (GF and CF). Other types of fibre also used but not as common are aramid and basalt fibres (AF and BF), see Table 1.

Table 1 Fibre properties (Hull and Clyne 1996; Net Composites 2011)

	E–modulus (GPa) axial	Tensile strength (GPa)	ν	ρ (Mg/m^3)
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

2.1 Fibre reinforcement materials

In terms of volume, GF are the most common type of reinforcement used in polymer matrix composites so called glass fibres reinforced polymers (GFRP). Glass fibre is the result of mixing sand, kaolin, limestone and colemanite together (André 2011). The variation in the proportion of each component results in different types of GF (E, C, R, S and T glass). E-type glass fibres are often used due to their good mechanical properties and low cost (2 €/kg in 2010). Carbon fibres (CF) are made by oxidation, carbonisation and graphitisation at high temperature of high content carbon precursor materials, which are mostly pitch, cellulose or polyacrylonitrile (André 2011). The latter is the most commonly used one. It leads to carbon fibres with the highest mechanical properties with regard to strength and stiffness. By varying the temperature during the graphitisation process from 2600 to 3000 °C, high strength (HS) or high modulus (HM) fibres can be produced. CF is more expensive than GF (20–60 €/kg in 2010), but they also have much better mechanical properties. Aramid fibres (AF) are an organic polymer (aromatic polyamide) product, produced by the mixing and reaction of aromatic diamines and aromatic diacid chlorides. There are two main aramid fibre types: para-aramid and meta-aramid fibres. They have very good mechanical properties and good resistance to impact. Aramid fibres are also fire, heat and chemical resistant (André 2011).

Basalt fibres (BF) are very interesting materials especially as reinforcement of concrete and timber. Basalt is a naturally occurring material, produced from the solidification of volcanic lava. It is primarily composed of silicon dioxide, and is the most abundant rock found in the Earth's crust. Russia has nearly endless reserves, though with only 30 active quarries (Christian and Shebli 2012). Other countries with volcanic areas also contain large basalt reserves. However, as the chemical content differs by location, one of the greatest challenges for the use of basalt materials is a relatively high variation in mechanical properties. In order to produce a usable form of basalt, fibres are extruded and spun from molten basalt rock at temperatures of between 1300 and 1700 °C, with diameters generally of 13–20 µm (Patnaik 2009). Mesh, fabrics and reinforcement bars are commonly made of BF, but not yet laminate which would be the most useful as a reinforcement material for timber and glulam beams.

2.2 Resins

The resins used as matrix of FRP products can be classified into two families: thermoplastics and thermosets. The mechanical properties of some of the most commonly used resins are listed in Table 2. Epoxy resins are the most common ones used together with CF to produce CFRP.

3 Reinforced timber beams

A number of reinforcement systems have been developed by different research teams around the world and eight of these were compared, examined and presented by André (2011). The majority of tests have been carried out on glulam beams. The most common configuration is to bond different amounts of FRP reinforcement of different types to the tension side of the beam to increase the flexural strength and stiffness. Type and the amount of reinforcement (percentage of the cross-section), possible failure modes, design models, fire protection and aesthetic features of the reinforcements have all been investigated and reported in the literature (Van de Kuilen 1991; Tingley 1996; Hernandez et al. 1997; Johns and Lacroix 2000; Romani and Blass 2001; Fiorelli and Dias 2003; Borri et al. 2005; Jacob and Garzon Barragán 2007). Reinforcing glulam beams on both tension and compression sides is the most effective configuration in order to improve stiffness and strength with the least amount of FRP, and contributing to the most ductile behaviour of timber in compression (Kliger et al. 2007).

3.1 Design models

Analysis of FRP reinforced beams loaded in bending is based on classical beam theory and well-established material properties for timber/glulam and strengthening materials. Apart from the basic assumption that plane sections remain plane, there are some additional assumptions such as: full interaction between the beam and the strengthening composite material, no de-bonding between

Table 2 Matrix properties (Hull and Clyne 1996; Net Composites 2011)

	E (GPa)	$\sigma_{\max}$ (MPa)	$\varepsilon_{\max}$ (%)	N	ρ (Mg/m^3)
Thermoplastics					
Polypropylene (PP)	1.0–1.4	20–40	300	0.3	0.9
Polyetheretherketone (PEEK)	3.6	170	50	0.3	1.3
Polyamide (PA)	1.4–2.8	60–70	40–80	0.3	1.14
Thermosets					
Epoxy (EP)	2–5	35–100	1–6	0.35–0.4	1.1–1.4
Polyester (UP)	2–4.5	40–90	1–4	0.37–0.39	1.2–1.5
Vinylester	3	70	5	0.35	1.2

wood material and FRP occurs and that the FRP behaviour is linear elastic until failure is assumed. Timber is normally treated as elastic and brittle on the tension side and either linear or non-linear on the compression side. However, in order to determine the ultimate moment capacity, all the possible failure modes must be considered. Four different failure modes are needed to be taken into account in the modelling. The first and second are tensile failure of the glulam when (i) the beam is in a linear-elastic state, and (ii) the tension side is in linear-elastic state while the timber has started to yield in the compression zone. The third mode is compressive failure (the compressive strain is too large) before tension failure; this occurs when the beam is heavily reinforced on the tension side. The fourth mode is rupture of the reinforcement. There are some other possible failure modes that can happen but are in general not included in models; these are failure of the adhesive and compression failure of the reinforcement as a result of buckling of the reinforcement fibres in the compressive zone. Another possible failure mode is the shear failure of the beam. Shear failure is normally checked for the actual loading arrangement and can be decisive for short beams or heavily reinforced sections.

The deflection of strengthened beams (in the serviceability limit state) can be calculated using regular linear elastic methods with full interaction between the timber and the strengthening laminate, i.e., there is no significant slippage. The Steiner's rule was used to calculate the stiffness of the composite section (Van de Kuilen 1991). The load-bearing capacity in the ultimate limit state can be more accurately estimated using plastic design methods since the compressive side may "yield" before the tensile side breaks.

The classic assumption is that the strains are linearly distributed over the height of the beam. The calculation method is iterative. An assumption is made for the position of the neutral axis. The failure strain of the tensile face can be estimated from the bending strength and the modulus of elasticity, the corresponding strains in the compression zone of the timber and the strain in the composite laminate can be calculated with the theory of intercepting lines. The yielding strain on the compression face of the timber can be calculated from the compressive strength and the elastic modulus. The internal forces, shown in Fig. 1, are calculated from the stress distribution in the cross-section and they must fulfil the equilibrium condition for the internal forces:

$$F_{c,T} + F_{t,T} + F_{t,L} = 0 \tag{1}$$

The calculation is repeated for different assumptions of the position of the neutral axis until the above condition is fulfilled. The bending resistance is then calculated by applying Eq. 2.

$$M_R = F_{t,T} \cdot e_1 + F_{t,L} \cdot e_2 \tag{2}$$

3.2 Strengthening the tension side

Strengthening of only the tension side of a timber beam improves both stiffness and ultimate load-bearing capacity; however, it is not as effective as strengthening both sides, i.e., tension and compression. However, that is often the only option for many beams in existing structures where the compression sides are covered by flooring, for example. It is worth mentioning that interaction between beams and flooring (full or partial, through friction, for example) contributes to improve the performance. Schober and Rautenstrauch (2005, 2006) reported on strengthening tests on old spruce cracked timber removed from a more than 100 years old residential house in Bavaria, Germany. The amount of laminate (S&P 150/2000) glued on the tension side of some beams was only 0.24 % of the average cross-section. Based on the tests results, this small amount contributed to increasing bending stiffness and strength by 7 and 12 %, respectively.

3.3 Strengthening both tension and compression sides

Jacob and Garzon Baraggán (2007) and Kliger et al. (2007) studied the amount and effect of CFRP reinforcement on stiffness and ultimate load-bearing capacity using non-linear models. Plastic behaviour of timber in the

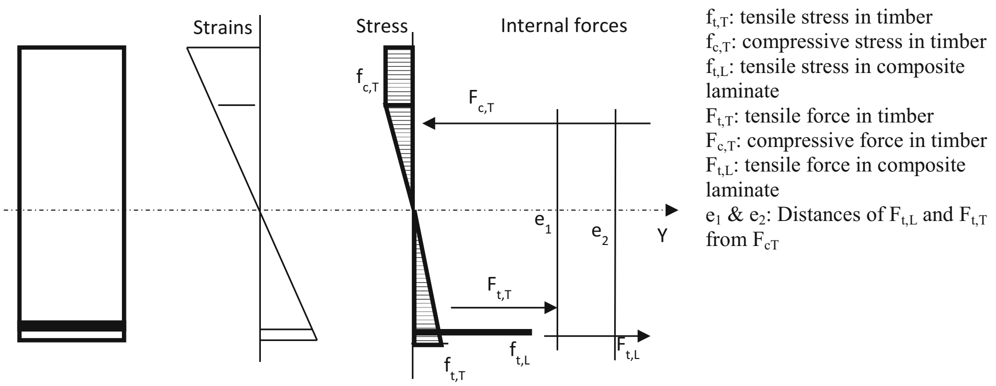


Fig. 1 Elastic-plastic design calculation model proposed by Brunner (2008)

compression zone was included as nonlinearity in the model. Using this model in Matlab environment, the global behaviour was simulated under stepwise strain increment and in each step the failure criteria of each component were checked.

The effect of different amounts of reinforcement as well as the distribution of the reinforcement between the tension and compression sides of the beams was studied using the model. The study included the influence of the reinforcement ratio between the tension and compressive sides of the beam on the ultimate moment capacities and elastic stiffness. The total reinforcement percentages of the beam's cross-sections ranged from 1 to 5 %. The results from this study showed that for stiffness, as expected, the higher the percentage of reinforcement the higher the stiffness of the beam. The highest increase in terms of stiffness can be gained when placing half of the reinforcement on the compressive side and half of it on the tension side. The results for ultimate bending strength showed the same results when increasing the amount of reinforcement, the more reinforcement the higher the ultimate bending strength, at least up to a level of 5 % of reinforcement. However, the results indicated that for the ultimate bending strength it is better to have only between 25 and 30 % of the reinforcement on the compressive side of the beam. The shear limit for a standard loading arrangement according to EN 408 (four point bending and span of 18 times beam's height) shows that it is not worthwhile to reinforce a beam with much more than 2 % of reinforcement. A higher level of reinforcement leads to shear failure before the ultimate bending strength is utilised. In the same study (Jacob and Garzon Baraggán 2007), various experimental series were conducted with various loading arrangements.

An experimental study was carried out by Kliger et al. (2008) to verify the predictions produced by Jacob and Garzon Baraggán (2007) and five configurations were tested. Glulam beams, L40 (corresponds to GL30c), of dimensions 115 × 200 × 4000 mm^3 reinforced using the near-surface mounted (NSM) technique were tested. Two un-reinforced beams were also tested to obtain a reference value for the strength and stiffness. The reinforcement was placed along the whole length of the beams, i.e., continuing over the support and the beams were loaded in four-point bending configuration. The increase in the ultimate moment capacity was between 57 and 95.8 %. The tests also showed that the introduction of reinforcements in the cross section reduces the variability in results. The results from un-reinforced sections varied a great deal in their stiffness (almost 15 %) as well as ultimate load carrying capacity (about 17 %). In the reinforced sections, however, the variability was much smaller, as the reinforcements contributed to the overall performance. The two beams reinforced with CFRP showed excellent similarity in their properties. The stiffness variation was less than 1 % while the ultimate loading capacity varied by 8 %. The reduction in variability is consistent with the findings of several studies (Gentile et al. 2002; Gentry 2011; Raftery and Harte 2011). All the reinforcing schemes had a positive effect on the overall ductility of the beams. The ultimate failure was in tension for almost all beams when the timber reached its tensile limit, except for heavily reinforced beams where the failure was in shear.

3.4 Improving ductility by correct amount of reinforcement

The ductility was caused by two factors in the tested beams as reported in Kliger et al. (2007). Reinforcement on the tension sides leads to yielding of the glulam on the compressive side and possible buckling of CFRP. By controlling the reinforcement percentage on the tension side of the beam it is possible to induce a desired amount of yielding on the compressive side of the beam. The failure mode such as buckling of the CFRP laminates utilises the compressive side of the beams to a maximum. At high-load levels, it is possible to induce fibre buckling in the CFRP laminates, as shown by André (2011). The mechanism of compression failure in CFRP-reinforced wood specimens was studied by André et al. (2013), using a digital image correlation system (ARAMIS). In particular, kinkband formation and propagation was investigated in the wood and in the CFRP. The material model for CFRP-reinforced wood specimens under compression loading was determined in terms of the compression modulus (the theoretical average modulus between modulus of wood material in compression and modulus of CFRP), the compressive strength and steady-state stress, for the so-called beam-block specimens with reinforcement placed inside the wood. It was shown that the amount of reinforcement is linearly linked to these mechanical properties. These relationships can be used to extrapolate a material model for a specific reinforcement system with different amounts of CFRP reinforcement.

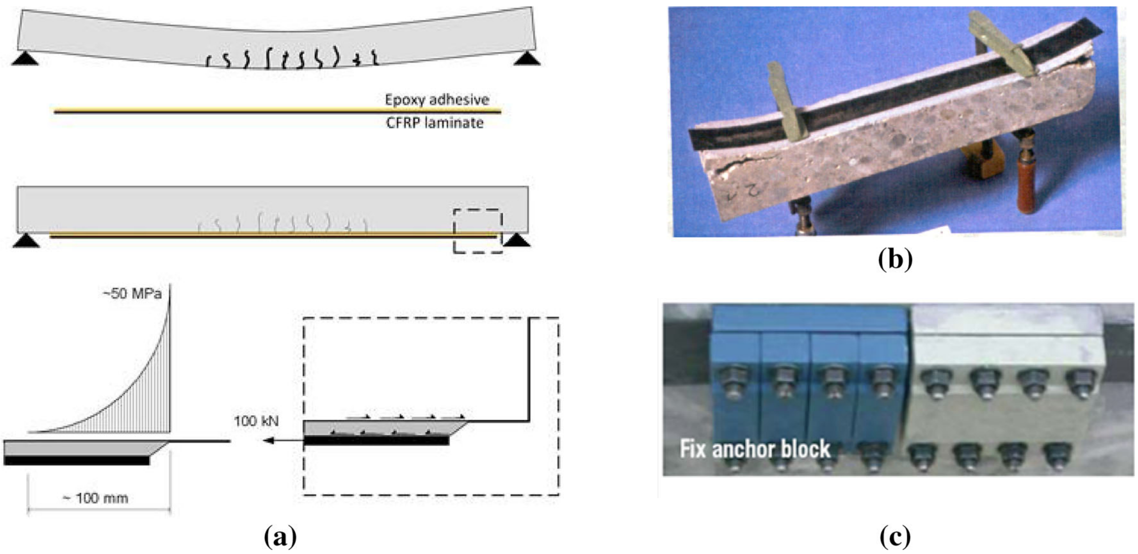
4 Pre-stressed reinforced glulam beams

4.1 Overview

The pre-stressing of the laminate is a particularly effective method to improve the performance of strengthened timber or glulam beams in the serviceability limit state. The eccentric pre-stress on the tension side of a beam induces significant compressive stresses, which opposes the tensile stresses due to the external loads. Pre-stressing of a beam also influences the deformation of the member. Large enough compressive force may camber a beam in the upward direction which can offset the deflection due to the external loads. The amount of reinforcement can be less than that of un-pre-stressed systems as the material could be utilized to 100 % and therefore the method is much more cost efficient. In passive or slack reinforcement, the ultimate strength of the FRP is generally not reached as the failure generally occurs in the timber material. Pre-stressed (CFRP) laminates are commercially used to strengthen concrete and steel structures (especially old structures in cast iron). General advantages of pre-stressing any FRP systems over un-pre-stressed systems are:

- Need for less FRP strengthening material
- 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

Until now the pre-stressing systems were not successfully applied to timber mostly due to debonding of the FRP laminate as a result of concentrated shear stress at the laminate end. Using pre-stressed FRP laminates for strengthening and repair of structures presents several challenges, primarily due to difficulties associated with applying the pre-stressing force and bonding of the pre-stressed FRPs to the beams. One of the greatest challenges encountered is the development of high shear stresses at the ends of the pre-stressed FRP laminate which can easily exceed the strength of the adhesive used for bonding and the wooden or concrete substrate material, as shown in Fig. 2a. Shear strength both in conventional adhesives used in composite structures and in timber is well below



(a)

(b)

(c)

Fig. 2 **a** Formation of high shear stress at the area close to the end of pre-stressed laminate, **b** debonding of a pre-stressed FRP-laminate attached to a concrete beam and **c** mechanical device to anchor pre-stressed laminates (www.sika.com)

25 MPa, whereas the shear stress at the ends can typically reach values of around 40–50 MPa. These high shear stresses at the ends of the pre-stressed FRP laminate may result in debonding of the FRP laminate from the structural member (see Fig. 2b) from the test conducted on concrete. Another challenge, more specific to pre-stressing glulam beams, is the low shear capacity in the timber. If the shear stress in the bond line between timber and FRP laminate exceeds this limit, failure may occur due to very small pre-stressing loads in the laminate. Debonding limits the utilisation of the strengthening system and can be characterised by a sudden separation of the FRP laminate from the structural member rather than a ductile behaviour. Mechanical anchors are usually used to solve the problem of high shear stresses at the FRP laminate ends (Fig. 2c). However, there are several problems associated with using a mechanical anchoring system which could still be considered as a major limitation.

Mechanical anchors are in many cases rather complicated, time-consuming and costly to manufacture, install and inspect. They often need to be manufactured with very small dimensional tolerances for the specific structural member to be strengthened. The structural member on which they are mounted often needs to be modified (a part of the structural member may need to be cut out and removed and bolts may have to be drilled into the structural member and fixed in place using adhesive or mortar bonding for example). The mechanical anchors may be susceptible to moisture and dust accumulation which may result in the corrosion of the anchoring system. Furthermore, galvanic corrosion may take place when metal anchors are used if the CFRP laminate comes into contact with the anchor there. A major specific problem related to using mechanical anchors in timber beams is that usually high clamping forces are applied on anchors and due to creep problems in wood they usually lose their clamping effect.

4.2 Design models

Design models for timber beams strengthened with pre-stressed FRP laminate have been presented by a number of researchers. A pre-stressing force can be considered as an axial compressive force acting on the cross-section. If the pre-stressing force is applied to an unrestrained beam, the lateral buckling of the beam must be checked. Brunner and Schnueriger (2007) describe a calculation model for the case of a pre-stressed FRP laminate bonded to the tension side of a beam using an iterative approach for the moment capacity and a linear elastic- perfectly plastic model for timber in compression. Their plastic design model, see Fig. 1, can be easily adapted to accommodate a pre-stressing force. The force $F_{t,L}$ in the laminate is increased by the value of the pre-stressing force initially applied (minus the time-dependent losses for shrinkage and creep of the timber). A full interaction between the pre-stressing laminate and the timber beam is assumed. Triantafillou and Deskovic (1992) considered the same situation as did Persson and Wogelberg (2011), but used a different bilinear model for the compressive response. Brady and Harte (2008) presented a closed form expression for the moment capacity of pre-stressed glued-laminated beams incorporating a lamination below the FRP, where the timber in compression was modelled using a bilinear model with a falling branch post-yield.

4.3 Methods of pre-stressing

4.3.1 *Dagher et al. (2010) method by releasing the pre-tensioning force during wet bond line*

Dagher et al. (2010) tested 6.7 m long glulam beams with cross-section width (b) times depth (h) of 130 mm × 305 mm with 1 % GFRP laminate reinforcement bonded to the soffit using a PRF adhesive. The GFRP laminate was placed over the steel tube and clamped at its ends between two steel plates that were anchored to the steel supports. A pre-stressing force of 98 kN, corresponding to 30 % of the ultimate tensile strength of the laminate, was applied to the laminate using hydraulic jacks at both steel supports. The 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 to apply an average clamping pressure of 1.0 MPa. 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. The strength of the pre-stressed beams was found to be 95 % higher than unreinforced beams and 38 % higher compared to reinforced beams with un-pre/stressed laminates. The average pre-camber of the beams was 10.9 mm, which can be offset against the allowable deflection.

4.3.2 *Lehmann et al. (2006) pre-cambering of timber*

An alternative method proposed by Lehmann et al. (2006) involved the pre-cambering of the timber before installing the FRP reinforcement. This is achieved using an adjustable prop located at the centre of the beam. This approach has the additional advantage of inducing a triangular bending moment distribution in the beam due to the prop force resulting in a low, constant shear stress in the glue line. Large specimens with cross-section width (b) times depth (h) of 120 mm x 160 mm were pre-stressed upside down. The desired pre-cambering of the beams during the production was achieved with the testing machine. The curing of the adhesive was done at elevated temperatures. The Sika Carboheater system was used in this study. The system works by sending an electric current through the CFRP lamellas which results in elevated temperature due to electrical resistance of carbon fibres. The temperature was controlled with a k-wire in the glue line. The temperature of the epoxy glue line was raised over 30 min to 90 °C and remained at this level for another 60 min. Clamps were used to prevent the FRP laminate from lifting due to the vapour pressure. This vapour pressure resulted from the heating of the timber (MC 12 %) near the glue line. The clamps and the load were released after the glue line was cooled down to 40 °C. The estimated increase of the load bearing capacity in bending was about 30 %. The total contribution (including the camber) of the reinforcement to the service limit state was around 40 %. This method may not be suitable for large beams as the prop force required may be too great.

4.3.3 *Gradient pre-stressing by curing the epoxy from the middle of the beam*

Stöcklin and Meier (2003) developed a method to apply pre-stressed FRP strips to concrete structures at EMPA (Swiss Federal Laboratories for Material Testing and Research). In this method, the FRP strip is first pre-stressed then bonded to the beam to be strengthened. A special pre-stressing device as illustrated in Fig. 3 was designed to perform the pre-stressing. It consists of two wheels which are connected to a beam of the required length, as shown in Fig. 4.

The FRP strip (1) is wrapped around the wheels (2) and clamped at its ends (3) as shown in Fig. 3. The strip can be pre-stressed by rotating one or both wheels (3a) or displacing the wheels (3b). As one can see in Fig. 3a, the pre-stressing device with the pre-stressed FRP laminate is temporarily mounted to the structure and can be pressed against the structure with a constant pressure by means of an air-cushion (5) between the FRP laminate and the beam. As described by Meier et al. (2001), gradual anchoring is achieved by first bonding a fully pre-tensioned section in the middle of the FRP strip at mid-span. A system of electric heating is used to speed up curing of the adhesive in the bonded section within the pot life of the adhesive. After curing the central part 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.

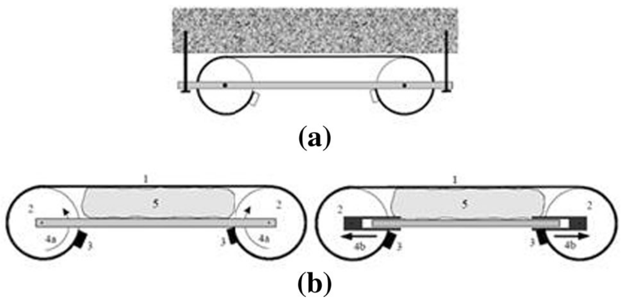


Fig. 3 Principle of the pre-stressing device designed in EMPA (Stöcklin and Meier 2003)

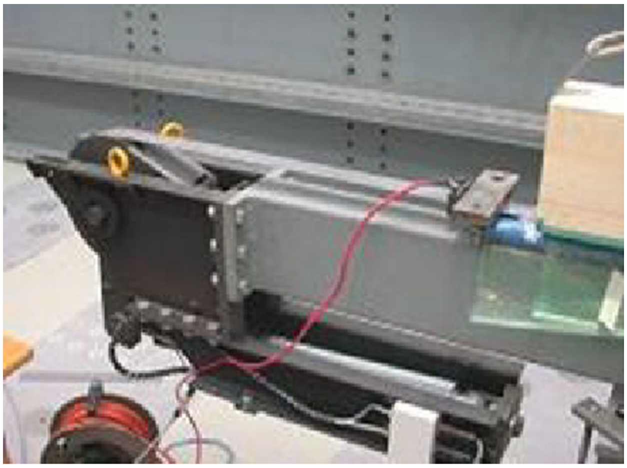


Fig. 4 Pre-stressed FRP-laminate being attached to a timber beam with the EMPA device (Brunner and Schnueriger 2007)

Brunner and Schnueriger (2007) used this device to strengthen glulam beams with pre-stressed FRP-laminates (Brunner 2008). The FRP laminate was coated on one face with the epoxide-based adhesive and then stressed by the machine with the coated face facing the bottom face of the timber beam. The FRP was attached to the bottom surface of the beam at mid-span by activating the adhesive in this zone with heat. After several minutes to allow the curing process, the pre-stressing force was slightly reduced and the next segment of the FRP was attached to the beam, moving towards both beam ends. In this manner, the pre-stressing force could be uniformly spread over a certain length at both ends of the beam. The whole process may take half a day for a large beam.

4.3.4 *Step-wise pre-stressing method developed at Chalmers*

A drawback involved in the device developed at EMPA was the rather long time needed to complete each step of pre-stressing and also complications and precision involved in releasing the pre-stressing force which at the end limited the total practical number of steps and thus maximum pre-stressing force to be applied to the laminate. A new method for application of pre-stressed FRP laminates was developed at Chalmers University of Technology (Haghani and Al-Emrani 2014).

The idea of this method is to control the magnitude of the interfacial stresses by manipulating the pre-stressing force profile in the laminate. However, 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. In other words, the pre-stressing force is gradually built up in the laminate instead of pre-stressing to the maximum level and then releasing the force. This is achieved through gradual linking of the pre-stressing force at discrete points along a certain length at the laminate end, the so-called anchorage length (cf. Figure 5). The anchorage length for the one step pre-stressing is very short, i.e., the length over which the shear stress becomes zero resulting in high interfacial shear stresses. By applying the stepwise pre-stressing, the anchorage length is extended by transferring the pre-stressing force in several steps, here into ten steps as an example which results in transfer of the pre-stressing force over a longer length and thus low interfacial shear stress. In each step the magnitude of the axial force in the laminate is constant. The gradual accumulation of the force in each interval will give a smaller slope (α_2) to the axial force profile compared to the case in which the pre-stressing is done in one step (α_1). As the magnitude of the shear stress has a direct relationship with this slope, the smaller the slope, the lower the shear stress. 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.

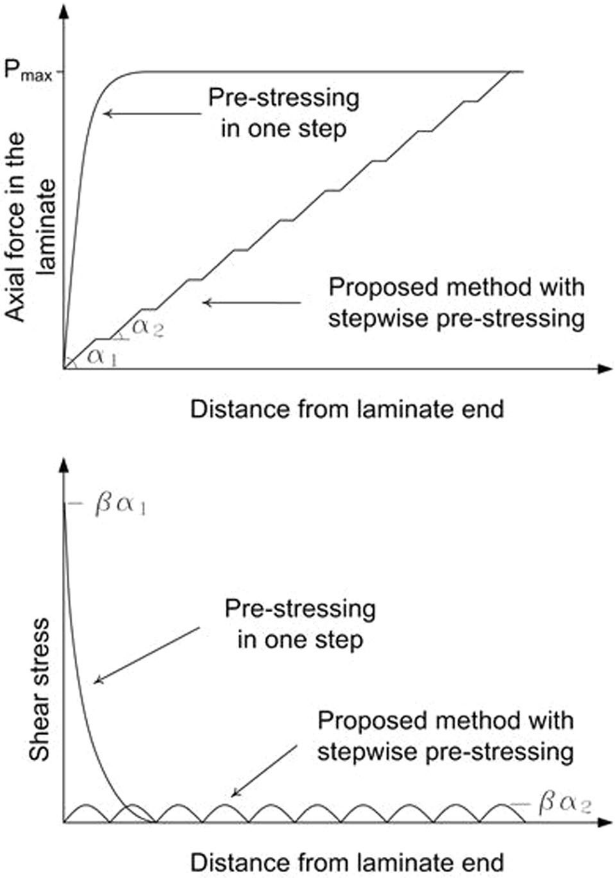


Fig. 5 Relation between distribution of axial pre-stressing force and shear stress according to the traditional pre-stressing method and the proposed step-wise method

Applying the pre-stressing force in this manner can be done in two ways:

1. through stressing the beam itself with a varying force profile similar to that in Fig. 5, bonding the laminate in un-pre-stressed state and eventually releasing the force in the beam. In such a case, the pre-stressing force in the beam, with the pattern, will be shared by the laminate.
2. By using a special device which is illustrated in Fig. 6.

The device consists of a number of tabs, here ten tabs, connected to each other using a series of springs. The stiffness of the springs is designed so that they deliver an equal portion of the total pre-stressing force to each tab, here 10 %, and eventually to the laminate. The device is connected to the CFRP laminate via a medium, e.g., a thin

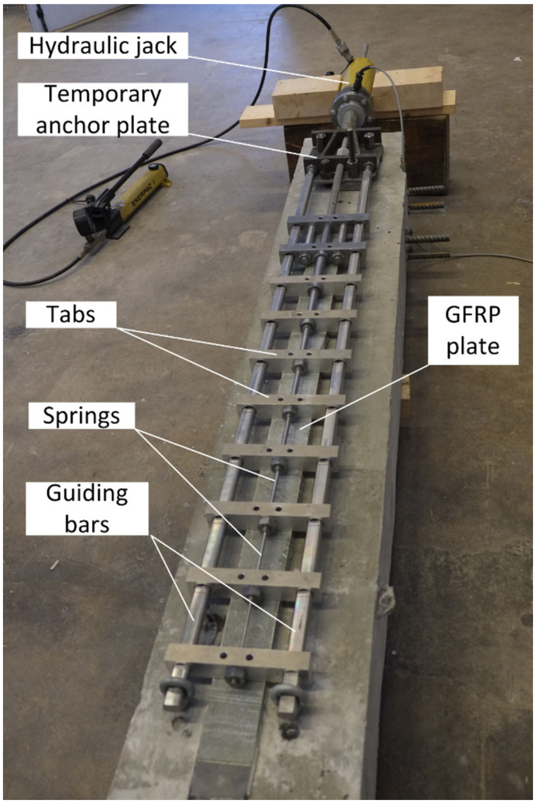


Fig. 6 Glass fibre (GFRP) laminate bonded to CFRP laminate with small moulded nuts where the screws will be connected to the device

glass fibre plate, which is bonded to the CFRP laminate and screwed to the device as shown in Fig. 6.

In an experimental study carried out at Chalmers, glulam beams were strengthened using the first alternative. Temporary posts were used to pre-stress the beam in six steps. Two beams with cross-section width (b) times depth (h) 120 mm × 200, strength class GL30 h, were pre-stressed with near-surface-mounted CFRP laminates; each with one laminate. The length of the beams was 4 m and the CFRP laminates were applied over the total length of the beams. The first beam was strengthened with a laminate provided by STO, type S624 (cut into 30 mm × 2.4 mm) and a pre-stressing force of 70 kN was applied to the temporary pre-stressing steel bars and the second beam with a Sika laminate, type S612 (cut into 30 mm × 1.2 mm) and a pre-stressing force of 50 kN in the pre-stressing bar. The total pre-stressing force *F* was applied to a pre-stressing bar passing through temporary posts mounted on the beams, as shown in Fig. 7a. The pre-stressing force in the bar was then reduced to zero at the end posts by gradual reduction in each step. Prior to mounting the posts, the laminate was placed in a premade groove filled with epoxy adhesive, see Fig. 7a. After curing of the adhesive, the force in the bar was released. The resultant profile of the axial strains in the laminate in the second beam is shown in Fig. 7b. It can be clearly seen that the pre-stressing force is linked stepwise in the beam as it was originally designed. By changing the number of steps, a more or less gradual force profile can be obtained. The two beams plus an un-strengthened beam (reference) of the same dimension were loaded to failure using a 4-point bending configuration according to EN 408 (2003).

For the pre-stressing force in the steel rod (F = 70 kN), the increase in the strength in relation to the un-strengthened beam was 18 % while it was 11 % for the pre-stressing force of F = 50 kN. 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 rather limited, i.e., less than 10 % of the pre-stressing force in the bars is transferred to the CFRP laminate. Therefore, it is more effective if the pre-stressing force is directly applied to the laminate using the pre-stressing device as mentioned in the second alternative. The pre-stressing device, illustrated in Fig. 8, has been successfully used to install pre-stressed laminates with forces up to 150 kN in the laboratory to concrete beams. This device could easily be used on timber or glulam beams specifically in situ on existing structures.

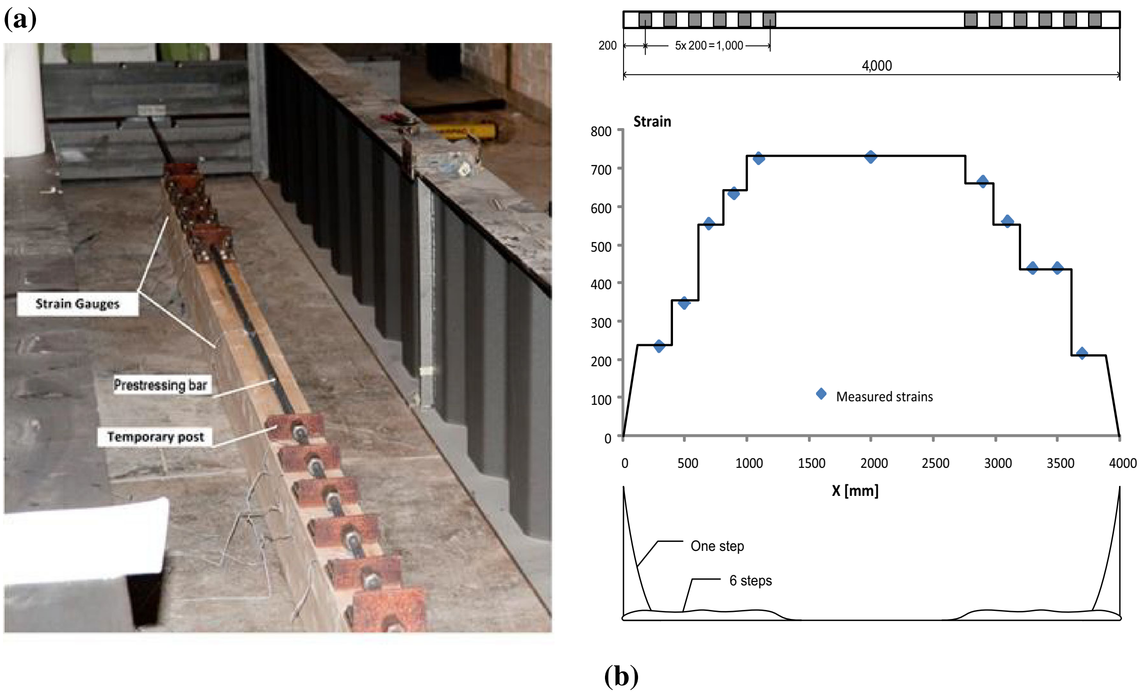


Fig. 7 **a** Adjustment of the posts before gluing the laminate. **b** Axial strain profile in the laminate after releasing the pre-stressing bar and the calculated shear stress from strain measurements due to stepwise pre-stressing compared to theoretical shear stress distribution without stepwise pre-stressing

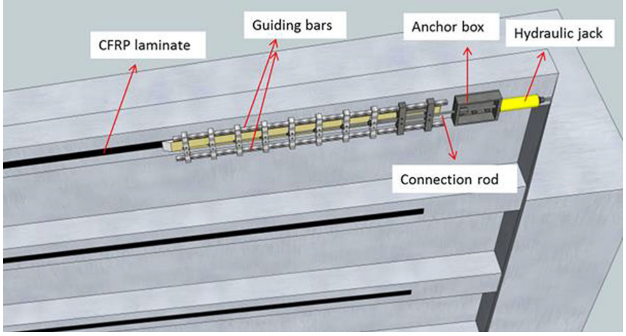


Fig. 8 Mounting the pre-stressing device on the structure using a set of temporary anchor box and guiding rails (The device is patented and owned by Tenroc Technologies AB)

5 Discussion and conclusion

Different methods of strengthening timber glulam or any other wood-based beams loaded in bending are presented. Despite the fact that the reinforcement of timber structures has been used for over 50 years, only recently, due to the introduction of various FRP to the construction market, the development of various strengthening systems has been accelerated.

When it comes to the ultimate limit state, often passive or slack reinforcement is sufficient. However, compared to pre-stressed FRP systems, it requires more FRP material to reach the same level of strengthening. The design of timber beams in the majority of cases is governed by serviceability limit state. In this state, when constructing new beams the simple way is to pre-camber the beams. However, when the building height and the total cost of a building project play an important role then it is often more economical to minimise the overall construction height. In such a case, pre-stressing timber beams in factory would be an interesting option. The method proposed by Lehmann et al. (2006) using pre-cambering of the timber before installing the FRP reinforcement and stepwise curing appears to be an interesting approach for glulam producers. However, when a beam needs to be strengthened on site, then the stepwise pre-stressing method, developed at Chalmers (Haghani and Al-Emrani 2014), offers a good solution.

The amount of reinforcement can be reduced by applying pre-stressed laminates as a strengthening system compared to slack reinforcement. It is also more efficient as the material could be utilised up to 100 %. The method is even more cost efficient if there is no need for permanent anchors at the end of the laminate. Various laboratory tests results published in the international literature showed that it is possible to increase the allowable bending stresses by 38 % for the pre-stressed GFRP-glulam beams relative to the reinforced GFRP-glulam beams without pre-stress and an approximately 95 % increase compared to un-reinforced glulam beams (Dagher et al. 2010). For new construction it is possible to reduce the glulam area by almost 25 % while still fulfilling the same deflection requirements (Christian and Shebli 2012).

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