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REVIEW

A Review on Strengthening of Timber Beams Using Fiber Reinforced Polymers

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ABSTRACT

Fiber reinforced polymer (FRP) has been used in the construction industry because of its advantages such as high strength, light weight, corrosion resistance, low density and high elasticity. This paper presents a review of bonding techniques adopted to strengthen timber beams using FRP to achieve larger spans. Different methods of bonding between FRP and timber beams have been summarized with a focus on the influencing factors and their effects as well as relevant bond-slip models proposed for fundamental understanding. Experimental investigations to evaluate the flexural performance of timber beams strengthened by FRP bars, sheets and wraps have also been critically reviewed to identify key influencing parameters. Limited research available on the shear performance of FRP reinforced timber beams have been analyzed to determine the influencing factors of the shear performance in timber-FRP beams. The paper finally presents an overall summary of the current-state-of-the-art and proposes some future research directions in the field.

KEYWORDS

Fiber reinforced polymer (FRP); timber beams; retrofitting; engineered timber; flexural properties

1 Introduction

Wood is one of the few natural renewable resources that can be used in the construction sector for major structural applications. In addition to its renewable characteristics, timber offers an attractive natural appearance and high strength-to-weight ratio when compared against traditional building materials such as concrete and structural steel [1]. Wooden house is reported to provide excellent thermal comfort as timber walls can mitigate indoor temperature changes caused by the fluctuations in external temperature. Wood and bamboo has been used in construction for centuries and can also be used in modern high-rise construction to complement other traditional building materials [2,3]. The use of hybrid design concepts that combine beneficial features of timber with those of steel and concrete are becoming common to make the most use of various material types for building sustainable infrastructure for future generations.

In recent years, bamboo has been used increasingly because of its good mechanical properties [4–6], but the types of bamboo that can be used in construction need to be further developed. The relatively rich variety of available timber can save resources on the premise of satisfying mechanical properties and appearance. Timber has good mechanical properties but as an organic anisotropic material, it offers significantly different properties depending on fiber orientation. Tensile and compressive strengths of timber are also considerably different, and these mechanical properties are higher along the grain, but they are significantly lower across the grain. To overcome natural limitations of wood, engineered timber products such as glulam, cross-laminated timber (CLT) and laminated veneer lumber (LVL) are often considered as a sustainable alternative to traditional construction materials. Especially, the recent surge in mass timber construction is predominantly contributed by the popularity of CLT and advanced manufacturing technologies for large-scale glulam structural components.

Strengthening of timber components is often envisaged as an option to enhance the structural resistance of major components such as beams and columns. The mechanical properties of bamboo or wood structure can be improved by chemical modification, and FRP reinforcement is relatively convenient and cost saving [7,8]. The reinforcement of beams can improve the bearing capacity and make the structure safer and meet higher performance requirements [9,10]. Fiber reinforced polymers is a kind of high performance material formed by mixing fiber material and matrix material (resin) in a certain proportion. It has the advantages of light weight, non-conductive, high mechanical strength, less recycling and corrosion resistance. Therefore, FRP can partially replace steel bars for the reinforcement of timber beams. FRP have been used for decades for structural retrofitting as well as for enhancing the structural resistance of concrete [11] and steel structures since 1980s. At that time, FRP was first used to strengthen concrete members, and in the 1990s, it was used in masonry, wood and steel structures [12]. FRP is also widely used in retrofitting of ancient buildings by strengthening damaged mortise and other damaged parts [13]. FRP strengthening could also improve the ultimate bearing capacity and flexural rigidity of timber beams. Various types of FRPs such as CFRP (Carbon Fiber Reinforced Polymer), GFRP (Glass Fiber Reinforced Polymer), AFRP (Aramid Fiber Reinforced Polymer), BFRP (Basalt Fiber Reinforced Polymer) etc. are currently available for structural retrofitting. Wolter et al. [14] studied the impacts of the type of fiber reinforcement on the resulting material properties of the fiber reinforced polymers (FRPs), Table 1 shows the mechanical properties of FRP measured.

Table 1: Properties of fibers reinforced polymers [14]

Name	Modulus of elasticity (GPa)	Tensile strength (MPa)	Density (g/cm^3)
BFRP	32 ± 0.7	685 ± 28	1.9
CFRP	59 ± 2.3	788 ± 29	1.5
GFRP	25 ± 0.7	411 ± 26	1.5

Extensive research on FRP for decades resulted in the emergence of new composites offering enhanced mechanical properties [15]. Researchers conducted numerous comparative studies to evaluate the relative performance of various types of FRPs that are commercially available in the market. The elastic modulus of BFRP is more compatible with wood and hence could offer superior bonding when used for strengthening [16]. CFRP offers higher tensile strength than both GFRP and BFRP; the tensile strength of CFRP could go up to five times higher than that of ordinary steel [17]. At elevated temperatures, BFRP is reported to perform better than GFRP [18]. GFRP was reported to be suitable for improving the bending resistance of glulam wood [19], effective bonding is one of the prerequisites for ensuring composite actions.

García et al. [20] reported that one-way CFRP reinforced timber beams produced better mechanical strength than two-way CFRP reinforced timber beams but the latter offered higher stiffness than the former [21]. Based on experimental investigation, Xiong et al. [22] reported that wrapping of FRP sheets around glulam members could limit the development of cracks and improve the strength, stiffness and energy dissipation capacity. FRP reinforcement can either be inserted into critical locations of structural elements during manufacturing or can be applied in the field using prefabricated conformable shells or by wet compaction [23]. The insertion of FRP into wooden beams can increase the load-bearing capacity and reduce the design size of the new structure [24]. FRP reinforcement technique can also be used to extend the span length of existing timber beams [25]. Shear connectors made from CFRP have also been successfully used in strengthening timber structures [26]. The use of FRP can enhance the elastic response of timber beams significantly [27], which is a key factor in designing larger structures using timber. Typically, the addition of FRP either as a wrap or reinforcement to wood components can improve their structural performance both in terms of strength and reliability [28], but it was recently reported that under the action of freeze-thaw cycles, FRP-coated timber specimens are more brittle than those at room temperature [29]. Flexible thin film solar cells can be attached or embedded on the surface of fiber-reinforced polymer (FRP) sandwich curved plate to form a new functional structure integrated with solar enclosures [30].

Timber is gaining widespread use in structural applications due to numerous beneficial reasons, one of which is its renewable nature. However, being a natural fiber, its mechanical properties often limit its application in large scale structures. Engineered timber is one of the possible solutions to this matter but the use of FRP is considered as an option to further enhance timber's mechanical strength for structural applications. FRP reinforced timber could play a significant role in future construction and this paper presents a review of relevant research and future research directions in the field. At present, the research progress of FRP reinforced timber beams mainly focuses on the improvement of the flexural performance. In this paper, the effects of bonding method, reinforcement method on the flexural, shear and creep properties of wooden beams, as well as the improvement effect of prestressed reinforcement on mechanical properties are compared, summarized and analyzed. The main aim of this paper is to draw some conclusions through the comparative analysis of different aspects, and provide reference for the future research and application of strengthening timber beams with FRP.

2 Bonding of FRP and Timber Beams

Bonding plays an important role in giving full play to the mechanical properties of components [31,32]. Timber is weak in tension and hence the flexural capacity of timber beams is often limited by tension failure when strength limit is considered. The other major issue with timber is its low stiffness, which results in excessive deflection; serviceability limit states are critical in timber engineering. These observations prompted researchers to use FRP to strengthen timber beams. The following subsections present an overview of different techniques employed to achieve suitable bonding between FRP and timber. A number of analytical models have also been proposed to simulate the observed mechanical response.

2.1 Bonding Methods

The bonding method of FRP and timber beams has an important influence on the mechanical properties of the components since appropriate bonding in essential for enhanced flexural resistance of timber beams. At present, the bonding methods of FRP and timber beams include bottom anchoring, externally bonded reinforcement (EBR), vertical near surface mounting (VNSM), horizontal near surface mounting (HNSM) and glued-in-rods (GIR). Fig. 1 shows the different bonding methods.

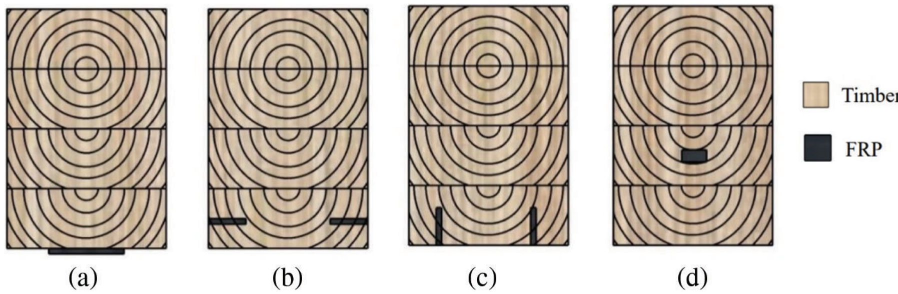


Figure 1: Cross-section of timber beams showing different bonding methods (a is EBR, b is HNSM, c is VNSM, d is GIR)

The performance of the adhesives has a certain influence on the effect of FRP reinforced timber beams, the main adhesives conclude epoxy resin, polyurethanes, phenolics, aminoplastics. Epoxy resin has excellent chemical resistance, especially alkali resistance, polyurethanes has high strength, tear resistance and wear resistance, phenolic resin has good heat resistance, fire resistance, water resistance and insulation, good acid resistance and poor alkaline resistance, amino resin has good drug resistance, water resistance and weather resistance. The resin matrix can be used as a protective agent [33]. The bond strength between wood and FRP also depends on geometric shape, boundary conditions, specimen arrangement, mechanical properties of wood, FRP size, etc. [34]. FRP is used either as a bar or as a sheet to reinforce timber beams, and the following sections will present additional insight into relevant bonding techniques.

2.1.1 Bonding between FRP Bar and Timber Beams

FRP bars have significant potential to enhance the flexural resistance of timber beams and hence this technique has attracted considerable attention from researchers. Cheng et al. [35] proposed an anchoring technique for local enhancement of glulam beams by anchoring FRP bars to the bottom layer. The FRP bars were attached to the bottom of the glulam using an epoxy resin adhesive layer, and then the ends were fixed by an anchoring device. This method showed enhancements in the mechanical properties and creep resistance of glulam, reduced the variability of properties of glulam, and reduced the cost of FRP as relatively less material was used for reinforcement. Biscaia et al. [36,37] carried out single lapping shear tests with near surface mounted (NSM) and other six additional anchoring methods to improve the premature delamination of CFRP reinforcement due to lack of bonding. The other six additional anchoring methods were externally bonded reinforcement on grooves (EBROG), CFRP spike anchors, short superposed metallic L-shapes, a steel plate at the CFRP free end, an embedded rectangular hollowed section at the CFRP free end, and through a limited embedded length of the CFRP laminate free end across the thickness of the timber. Obtained test results showed that the best anchoring methods were two overlapping I-shaped metal profiles or CFRP embedded in wood substrates. The bonding process between CFRP and wood was also analyzed assuming the bonding stress was parallel to the bonding surface. It was reported that the samples reinforced using the NSM technique showed the best strengthening effect. The NSM technique provided the best bond strength and the lowest effective bond length, and the failure load reached up to 72.4% of the CFRP rupture load, whereas EBR technique reached up to 55.0% of CFRP rupture load. Glued-in-rods (GIR) were also considered as an effective and convenient reinforcement method for timber beams. Khelifa et al. [38] developed finite element models to simulate the withdrawal resistance of FRP bars inserted into glulam by using three-dimensional continuous damage mechanics and cohesive zone modeling to conduct parametric analysis based on test observations. Vo et al. [39] investigated the method to accelerate the curing of the adhesive used for GIR. It was observed that when the Curie particles (Mn-Zn-ferrite particles) were added to the adhesive by induction heating and exposed to the high-frequency electromagnetic field, the bonding was rapid and more effective. The process of polymerization was accelerated due to elevated temperature, and eventually, the bonding performance was improved. Grunwald et al. [40] studied the effects of adhesives, bars, and wood using glued-in rods made from GFRP. Fig. 2 shows the observed five main failure modes.

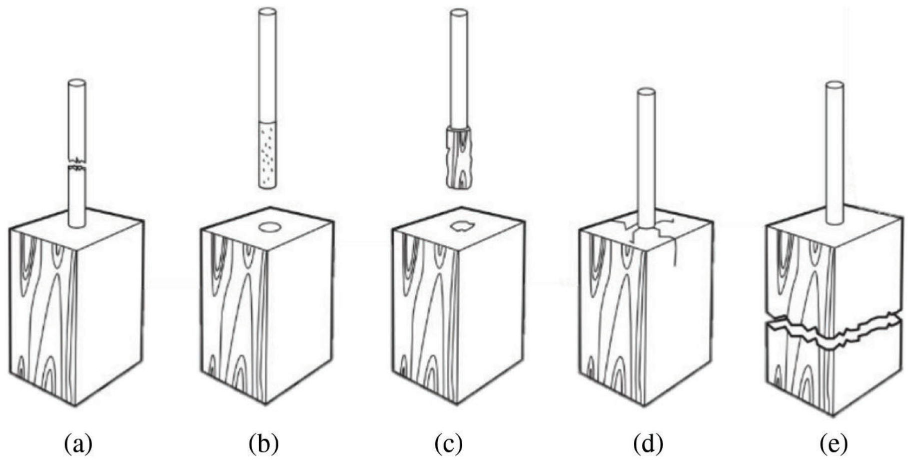


Figure 2: Various types of GIR failure modes reported by Grunwald et al. [40]: (a) Tensile failure of GFRP rod; (b) Failure of the adhesive; (c) Local shear failure of the timber; (d) Splitting of the timber; (e) Tensile failure of the timber member

Currently reported research on the bonding between FRP bars and timber beams primarily focused on techniques to achieve optimal anchorage mode and on the factors that influence bond characteristics. The properties of wood, FRP bars, and adhesives have been reported to have a significant influence on bonding. The bond stress, slip length, and bond length can be modeled using continuum mechanics to simulate test observations. The properties of the binder, bonding methods, and the contact mechanism between FRP bars and timber beams need further investigations to develop an in-depth understanding of design applications.

2.1.2 Bonding of FRP Sheet and Timber Beams

FRP sheets have been widely used for structural retrofitting of concrete structures for decades. Similar use of FRP sheets in wooden structures is also becoming common. The fundamental difference between FRP bars and sheets is that the latter offers a significantly larger surface for bonding when used in timber beams. The type and location of the FRP sheet and the grain direction of FRP relative to those of wood are the most important factors for the effectiveness of strengthening.

Fava et al. [41] conducted experiments to evaluate the influence of the bond length, the FRP type, and the relative orientation of fibers of FRP and wood. It was observed that the FRP sheet reinforced beams either failed at the adhesive-FRP interface or the adhesive-glulam interface. Compared with the linear elastic brittle tensile failure experienced by unreinforced plywood, the FRP reinforced beams showed ductile behavior [42]. Vessby et al. [43] used different FRP bond lengths, i.e., 50, 150, and 250 mm to study the effect of the bond length on the strength and stiffness of the structure, and it was reported that the capacity of the reinforced part increased with the increase of the bond length. Juvandes et al. [44] conducted four-point bending tests on CFRP sheet and timber bonds along the fiber direction using three types of orientations such as EBR, HNSM (horizontal near surface mounting), and VSNM (vertical near surface mounting) to determine the maximum anchorage length and the effective bonding length for the considered cases. Wan et al. [45] conducted a comprehensive experimental investigation using 86 samples of FRP reinforced wood to study the effects of adhesive type, FRP plate type as well as wood type on the bonding property.

Some of the key observations were as follows: the strength of the pultruded plate was higher than that of the wet coated plate, and softwood joints were damaged in wood, whilst hardwood joints were mostly damaged at different interfaces. Softwoods typically offer stronger bonding due to their low density, whilst hardwoods do not allow sufficient penetration of adhesives making the interfaces vulnerable. Kramár et al. [46] investigated the effect of using corrugated surfaces, as shown in Fig. 3, for enhancing the bond performance between FRP sheet and timber. Four-point bending tests were conducted on various types of specimens such as unreinforced rectangular beam, beams strengthened by wet application of FRP sheet as well as by using VARTM (vacuum assisted resin transfusion moulding) process, and two types of corrugated beams, i.e., unreinforced and strengthened by CFRP using VARTM process. Experimental results showed that the corrugated CFRP beams had the highest bending resistance due to strong bonding between FRP and the corrugated timber surface, as shown in Fig. 4.

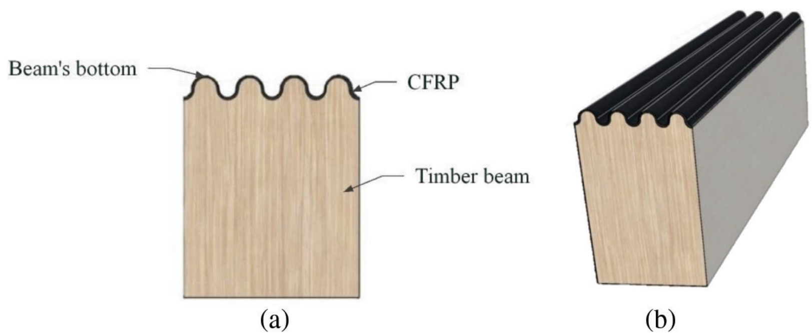


Figure 3: Corrugated beam with FRP sheet reinforcement [46]

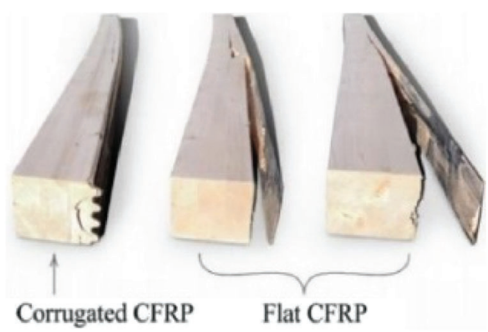


Figure 4: Failure modes observed in corrugated and flat beams reinforced by FRP sheets [46]

FRP sheets offer a larger surface for bonding and are easy to use for strengthening timber beams. However, this technique would require additional research to improve bonding. Softwoods typically offer better bonding but the wood itself is weak in tension. Hardwoods are much stronger in tension but the poor bonding between FRP and wood due to hard woods' higher density is a major drawback in composite action. Significant research would be required to find the effects of relevant design parameters, i.e., mechanical properties of wood, FRP, and adhesive; and enhancing the effectiveness of bonding between FRP and timber.

2.2 Bond-Slip Relationship Model

The brittle failure mechanism caused by FRP peeling failure is reported to commence at the early stage of beam loading [47], and hence, the bond between FRP and timber beams plays an important role in FRP strengthening. In most cases, the local bond-slip relationship is obtained by testing the entire bond length of the FRP-wood joint with the strain gauge attached to the FRP composite. Vahedian et al. [48] conducted bond strength tests on 136 specimens produced using two types of wood with different FRP layers, varying bond lengths and widths. They proposed a new theoretical model to predict the bond performance based on the obtained test results, as shown in Fig. 5.

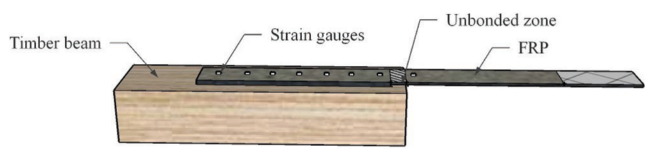


Figure 5: Schematic diagram of experimental setup for bond test [48]

The reinforcement effect is dependent on the position, applied load, and orientation of reinforcing bars. Ling et al. [49] obtained the distribution of bond stress and relative slip experimentally, and proposed the local bond stress-slip relationships along the bond lengths. It was reported that the local bond stress-slip relationship was different at different positions, and the local bond stress-slip curve near the loading end was generally smoother than that at the anchorage end. Geng et al. [50] used basic elastic theory to deduce FRP-timber bond shear stress formula under three types of loading. They also conducted parametric analysis and reported that the key influencing factors of interfacial bond shear stress of FRP-wood were vertically embedded FRP plate, FRP reinforcement ratio, and the elastic modulus ratio of FRP and wood.

The bond-slip relationship and debonding process of FRP-wood can be described by fundamental analytical models. Vahedian et al. [51,52] proposed a relationship between the bond strength, tensile strength, FRP-wood width ratio, and the bond length; the accuracy of the analytical model to predict the ultimate load was verified by using experimental results. They also proposed a new FRP-wood seam effective bonding length prediction model, which was also validated against relevant experimental results, as shown in Fig. 6. Biscaia et al. [53] proposed a trilinear bond-slip model, which can accurately describe the full range of debonding phenomena at the FRP-wood interface. Mulian et al. [54] experimentally investigated the dynamic characteristics of the debonding mechanism of FRP reinforced beams and also developed a finite element model for dynamic analysis of laminated beams to identify effects of various parameters on the dynamic response of laminated beams. Table 1 lists a number of analytical models that were proposed to capture bond-slip behaviour of FRP-wood. Table 2 shows some bond-slip models and makes comparative analysis.

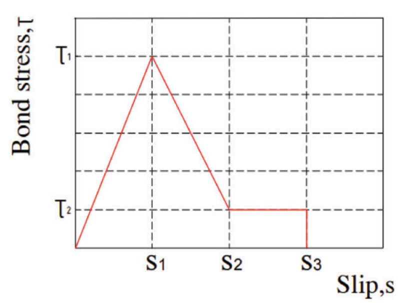


Figure 6: The bond-slip curve [52]

For the above model, the CMR can only calculate the stress in the rising section of bond stress, which is more accurate and has a smaller applied range than that of BPE. The Geng model [50] can calculate bond stress under three types of loading such as uniformly distributed load, one concentrated load in span, and two symmetric concentrated loads. Biscaia model [44] considers more of the properties of wood, it is more suitable for calculating the bond between FRP and wood.

Table 2: Bond-slip models

Name of model	Model
BPE model [50]	$\frac{\tau}{\tau_m} = \begin{cases} \left(\frac{s}{s_m}\right)^{\alpha} \; 0 \le s \le s_m \\ 1 - p\left(\frac{s}{s_m} - 1\right) \; s_m < s \le s_r \\ \frac{\tau_r}{\tau_m} \; s > s_r \end{cases}$
CMR model [50]	$\frac{\tau}{\tau_m} = \left(1 - \exp\left(-\frac{s}{s_r}\right)\right)^{\beta} \; 0 \le s \le s_m$
Geng model [50]	$\tau_r(x) = C_1 e^{\sqrt{\varphi x}} + C_2 e^{-\sqrt{\varphi x}} + \frac{\Psi}{\varphi} Q(x)$
Biscaia model [53]	$\tau(s) = \begin{cases} \frac{\tau_1}{s_1} S \; 0 \le s \le s_1 \\ \frac{\tau_2 - \tau_1}{s_2 - s_1} S + \frac{\tau_1 s_2 - \tau_2 s_1}{s_2 - s_1} \; s_1 < s \le s_2 \\ \tau_2 \; s_2 < s \le s_3 \\ 0 \; s > s_3 \end{cases}$

Note: τ_m is the maximum bond stress, s_m is corresponding sliding displacement. s_r means the slip value indicating that the bond-slip relationship gets into residual stress segment; α and p can be obtained by curve fitting of experimental results; for the CMR model, s_r and β are the parameters obtained from curve fitting of experimental results, for the third model, τ_r means the shear stress, C_1, C_2, φ, Ψ are undetermined coefficients, the bond-slip model's parameters are shown as the chart in the table.

Overall, the bond-slip model mainly studies the bond strength-slip displacement function relationship and the effective bond length model. The function equation was developed by fitting data points obtained from experimental investigations. In some cases, FE models were used to supplement experimental results to propose reliable models. More research and analysis are needed for the comparison of the stress-strain relationship between the bonding forces at different locations along the bond length and different stress modes.

3 Flexural Behavior of FRP Reinforced Timber Beams

FRP has a good strengthening effect on the flexural performance of timber beams. Wood is a natural material, and the uncertainty of its mechanical properties is much higher than metallic alloys or synthetic composites that are used in structural applications. FRP reinforcement can not only improve the bending performance of timber beams but also reduce the uncertainty of strength [55]. Splitting is one of the failure signs when the flexural bearing capacity reaches the limit. Splitting usually occurs due to short edge distance; rod misalignment; overloading perpendicular to the direction of wood grain [56]. D'Ambrisi et al. [57] found that CFRP was very effective in repairing old and new timber beams by conducting four-point bending experiments; the flexural capacity and stiffness of the FRP reinforced timber beams were greatly improved compared with the control beams, Fig. 13 shows the model of the flexural bearing capacity.

3.1 Timber Beams Reinforced with FRP Bars

Use of FRP reinforcing bars eliminates the chance of possible corrosion as experienced by traditional steel bars, and can also improve the stiffness, bending capacity, and ductility of timber beams. The main factors that affect the performance of FRP reinforced timber beams are reinforcement ratio, FRP type, FRP and wood length, grain direction, and contact area. Fig. 7 shows the timber beam reinforced with FRP bars.

Raftery et al. [58] observed that the section stiffness and the ultimate moment capacity increased by 18% and 31% by using 1.86% reinforcement ratio. Tajnik et al. [59] found that the flexural capacity of timber beams increased by 15% by using CFRP bars to strengthen the tensile zone. Liu et al. [60] experimentally compared rectangular poplar beams reinforced with BFRP of different lengths and found that the timber beams strengthened with 1900 × 50 mm BFRP bars showed the highest ultimate bearing capacity and maximum deflection, which respectively increased by 77.8% and 110.1% compared with those for the control beam.

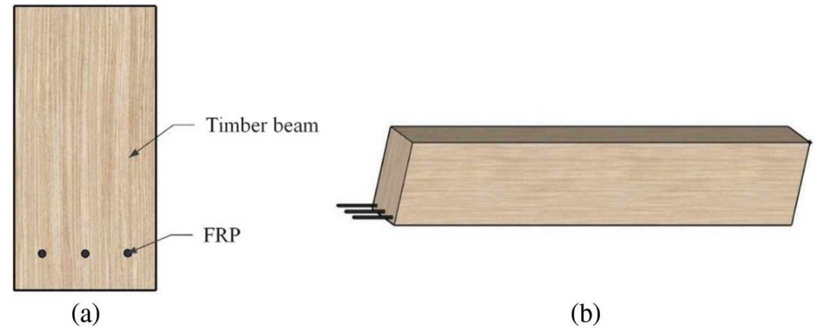


Figure 7: Schematic diagram of FRP reinforcement in timber beams (a is the sectional view, b is the longitudinal view)

Raftery et al. [61] carried out performance tests of reinforced glulam beams with different groove layouts as well as single-bar and double-bar FRPs of different sizes. They found that the mechanical properties of reinforced beams were improved by reducing the effect of stress concentration. According to Titirla et al. [62], the maximum load of the structure had a great relationship with the diameter of FRP bars and the grain direction of the wood. Al-Hayek et al. [63] compared beams reinforced with draped CFRP, straight CFRP bars, draped steel wire and straight steel wire. The results showed that compared to the control beam, the bending strength of four reinforcement types increased by 70%, 56%, 45%, 49%, respectively; the stiffness of specimens with draped CFRP bars increased by 10%, and that of beams with draped steel wires increased by 4%.

The study of FRP reinforcement has been mainly focused on the best reinforcement ratio, the influence of various factors on stiffness and the ultimate load-bearing capacity. For the study of the flexural performance of timber beams reinforced with FRP bars, the effect of the same reinforcement method using different FRP types was compared and analyzed. The matching degree between FRP and wood type in the mixed reinforcement of different FRP needs to be further studied. In addition to FRP and wood types, the reinforcement method also has a certain influence on the reinforcement effect. Under the same reinforcement ratio, the contact area can be increased by reducing the radius of FRP bars, the stress concentration can be improved to increase the bearing capacity, or the ultimate bearing capacity can be increased by anchoring to reduce the slip, etc.

3.2 Timber Beams Reinforced with FRP Sheet

The FRP sheet reinforcement can enhance the flexural bearing capacity, stiffness, and ductility of timber beams. The reinforcement effect depends on the properties of FRP fabric (thickness, elastic modulus, shear modulus), the number of layers, and the reinforcement method. Fig. 8 shows the timber beam reinforced with FRP sheet.

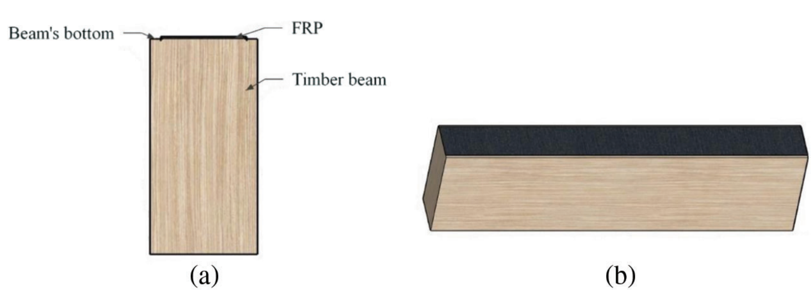


Figure 8: Schematic Diagram of FRP sheet reinforcement of timber beam (a is the sectional view, b is the longitudinal view)

Basterra et al. [64] carried out comparative experiments and found that when the reinforcement ratio of GFRP sheet reinforced timber beams was 1.07% and 1.6%, the average stiffness increased by 12.1% and 14.7%, and the bending capacity increased by 23%. Fig. 9 shows the FRP sheet reinforced beam section, Figs. 10–12 show the failure mode of this beams.

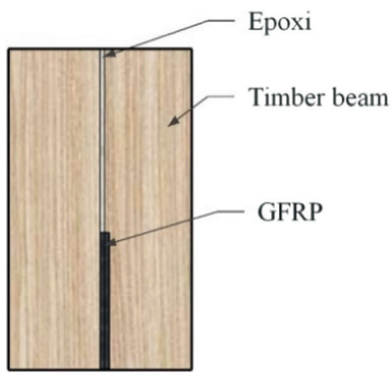


Figure 9: Schematic diagram of FRP sheet reinforced beam section [64]

Figure 10: Failure mode of unreinforced beams [64]

Figure 11: Failure mode of 1200 g/mm² GFRP reinforced beams [64]

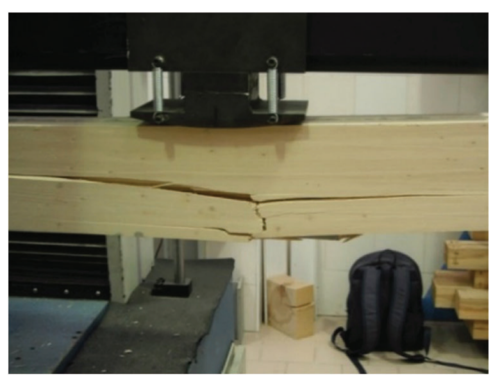


Figure 12: Failure mode of 2400 g/mm² reinforced beams [64]

Various researchers reported experimental investigations to identify influence of FRP sheet reinforcement on timber beams. According to literature, FRP reinforcement ratio (FRP layer number) appeared to be the main influencing factor. Yang et al. [65] studied six ordinary timber beams and 21 FRP, CFRP/GFRP reinforced timber beams. Based on the observation of bending stiffness, they found that when the reinforcement ratio was 0.37%–1.13%, the ultimate bearing capacity of the FRP reinforced beam increased by 17.7%–77.3% compared to the control beam, and when the reinforcement ratio changed, the failure mode of timber beams also changed. It shows that use of FRP sheet can either delay or eliminate the brittle failure of timber beams under tension. It also can reduce the influence of wood defects on the flexural performance to make full use of the compressive strength of wood and improve the stiffness and ductility of the structure. Zhang [66] studied the effect of FRP material type and reinforcement method on the performance of timber beams. The results showed that the FRP sheet enhanced the flexure bearing capacity of timber beams. At the same time, the single-layer carbon fiber sheet showed better ductility than that of carbon fiber plate, and the double-layer carbon fiber sheet had more stable mechanical properties than that of the single-layer carbon fiber sheet. Cao et al. [67] used three ordinary timber beams and 33 FRP beams to observe trends in ultimate load and bending stiffness. It was found that FRP improved the bending properties of timber beams. The main factors influencing reinforcement were the number of reinforcing layers, reinforcement type, and reinforcement method, etc. It should be mentioned that the CFRP reinforcement showed better effect than the GFRP reinforcement. Khelifa et al. [68,69] conducted experiments on flexural performance and found that compared with unreinforced beams, the flexural strength of beams reinforced with two-layer and three-layer CFRP increased by 41.82% and 60.24%, respectively. Andor et al. [70] used different amounts of CFRP to strengthen Norway spruce beams; statistical analysis showed that the bearing capacity and ductility increased by about 30%, and the elastic stiffness increased by 16%.

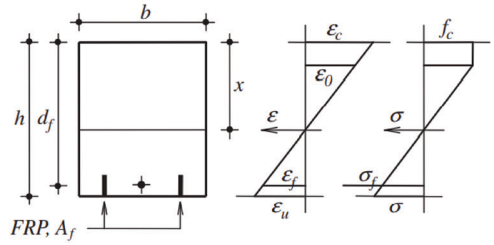
A number of models were proposed by researchers for calculating the flexural capacity of FRP reinforced timber beams. Shao et al. [71] proposed a formula for calculating the bearing capacity derived by using the analytical model for the compression zone of timber beam. It was found that the FRP layer can effectively improve the flexural capacity of timber beams, and an increase in the tensile zone is related to the number of reinforcement layers. An increasing range of compression zone is related to the setting mode and position of the reinforcement layer, and the transverse winding reinforcement is the best. Jia et al. [72] established the flexural bearing capacity and deflection equations of FRP reinforced timber beams under elastic and elastoplastic limit failure. Nevertheless, the calculated values obtained using the bending capacity and deflection formulas deviate considerably from the measured values, which highlights the need for further study. Table 3 shows some flexural bearing capacity models and makes comparative analysis.

Table 3: Flexural bearing capacity models

References	Model
[57]	When $\varepsilon_c \leq \varepsilon_0$, $M_R = E\varepsilon_u \frac{1}{h-x}$ $x = \frac{1}{bh+nA_f}\left(\frac{bh^2}{2} + nA_f + d_f\right)$ $I = \frac{bh^3}{12} + bh\left(\frac{h}{2} - x\right)^2 + nA_f(d_f - x)^2$ When $\varepsilon_c > \varepsilon_0$,

(Continued)

Table 3 (continued)

References	Model
	$M_R = \frac{bE}{6}\left[3\varepsilon_0 x^2 + (h-x)^2\left(2\varepsilon_u - \frac{\varepsilon_0^3}{\varepsilon_u^2}\right) + \frac{6n\varepsilon_u A_f(d_f-x)}{B(h-x)}\right]$ $x = \varepsilon_0\left[x - \frac{\varepsilon_0}{\varepsilon_u}(h-x)\right] + \frac{h-x}{2}\frac{\varepsilon_0^2}{\varepsilon_u} = \frac{\varepsilon_u(h-x)}{2} + \varepsilon_u\frac{E_f A_f}{EB}\frac{d_f-x}{H-x}$  **Figure 13:** Evaluation of the ultimate moment of timber beams strengthened with CFRP materials [44]
[65]	When $\rho\eta \le 0.05$, $M_u = \frac{(1-\alpha_{c,1}+0.5\rho)(1+3\rho\eta)}{6(1-\alpha_{c,1})}\cdot f_{tu}bh^2$ $\alpha_{c,1} = \frac{\left(-B_1-\sqrt{B_1^2-4A_1C_1}\right)}{(2A_1)}$ $A_1 = (1-m)(k_t+1)^{\ 2}$ $B_1 = -2k_t^2(1+\rho\eta) - 2(1-m)(k_t+1)$ $C_1 = (2\rho\eta+1)k_t^2 + 1 - m$ $k_t = \frac{\varepsilon_{ty}}{\varepsilon_y}$ $M_u = \frac{k_c(1+3\rho\eta)(1-\alpha_{c,2})}{6\alpha_{c,2}}\cdot f_{tu}bh^2$ $\alpha_{c,2} = \frac{\left(-B_2+\sqrt{B_2^2-4A_2C_2}\right)}{(2A_2)}$ $A_2 = 1 - k_c^2 + 2 + m(k_c-1)(k_c-1)$ $B_2 = 2k_c^2(1-\rho+\rho\eta)$ $C_2 = -k_c^2(1-\rho)^2 + 2\rho\eta$ $k_c = \frac{\varepsilon_{cy}}{\varepsilon_y}$
[71]	When $\varepsilon_t \ge \varepsilon_{tu,FRP}$, $M_u = \frac{1}{2}bf_s x_1\left(\frac{2}{3}x_1 + c\right) + \frac{1}{2}bx_2(f_s+f_c)\cdot(x_1+y+c) + bx_3 f_c\left(h-\frac{1}{2}x_3\right) - \frac{1}{3}bx_4^2 f_t$ When $\varepsilon_{cu} \le \varepsilon_t \le \varepsilon_{tu}$, $M_u = \frac{1}{2}bf_s x_1\left(\frac{2}{3}x_1 + c\right) + \frac{1}{2}bx_2(f_s+f_c)\cdot(x_1+y+c) + bx_3 f_c\left(h-\frac{1}{2}x_3\right) - \frac{1}{3}bc\sigma_t$ When $\varepsilon_t \ge \varepsilon_{tu}$, $M_u = \frac{1}{2}bf_s x_1\left(\frac{2}{3}x_1 + c\right) + \frac{1}{2}bx_2(f_s+f_c)\cdot(x_1+y+c) + bx_3 f_c\left(h-\frac{1}{2}x_3\right) - \frac{1}{3}bx_4 f_t$
[72]	In the elastic stage, $M_{ce} = \frac{\sigma_T^{ce} I_I}{c}$ $I_I = \frac{b}{3}c^3 + (h-c)^3 + nA_F(h-c)^2$ $c = \frac{0.5bh^2+nA_F h}{bh+nA_F}$ $n = \frac{E_F}{E_T}$ In the plastic stage, Tensile failure: $M_u = \left[\left(\frac{1}{3\gamma} - \frac{\gamma^2}{6}\right)(h-c)^2 + \frac{\rho_F nh}{\gamma}(h-c) + \frac{c^2}{2}\right]b\sigma_T^{ce}$

(Continued)

Table 3 (continued)

References	Model
	$c = \frac{(1+\gamma^2+2n\rho_F)h}{(1+\gamma)^2}$ $\gamma = \frac{\varepsilon_T^{ce}}{\varepsilon_T^{tu}} = \frac{\sigma_T^{ce}}{\sigma_T^{tu}}$ Tensile wrinkle failure: $M_u = \frac{3-\lambda^2}{6} c^2 b \sigma_T^{ce} + \left[\frac{1}{3}(h-c) + \rho_F n h\right] \frac{(h-c)^2}{c} b \sigma_T^{cu}$ $\lambda = \frac{\varepsilon_T^{ce}}{\varepsilon_T^{tu}}$

Note: ε_c is the compression strain of the timber, ε_0 is the elastic limit of the compression strain, x is the depth of the neutral axis, b and h are the sectional width and height of the beam A_f is the cross-section area of the CFRP strengthening material-, E is the elastic modulus of timber, I is the second moment of the homogenized cross-section area, M_R is the second moment of the homogenized cross-section area, ε_u is the failure strain of the timber in tension, B $\rho = A_r/A_w$ is the cross-section ratio of FRP to wood, $\rho = A_r/A_w$ is the MOE ratio of FRP to wood, M_u and M_{ce} are the ultimate bearing capacity, f_{tu} is the tensile strength of wood, and m is the ratio of the slope of the downward section of plastic compression in the curve of wood constitutive relation to its elastic modulus, ε_t, ε_{cu} and ε_{tu} are the tensile strain, ultimate compressive strain and ultimate tensile strain of wood, f_s, f_c are the yield strength and compressive strength of wood along the grain. I_I is the second moment of area, A_F is the area of FRP, E_F and E_T are the elastic modulus of wood and FRP sheet respectively, ρ_F is the distribution rate of FRP, ε_T^{ce} is the elastic ultimate compressive strain in the compression zone of wood ε_T^{tu} is the ultimate tensile strain in the lumber drawing zone σ_T^{tu} is the ultimate tensile stress in tension zone of the lumber, σ_T^{ce} is the equivalent maximum compressive stress. x_1, x_2, x_3 are respectively the height of elastic part, elastoplastic part and plastic part of the compression zone of the timber beam; x_4 is the height of the failure part in the tensile zone of the timber beam; y is the height between the centroid of the trapezoidal part in the cross-sectional stress distribution diagram and the ultimate compressive stress; f_t is the tensile strength of wood; b and h are the sectional width and height of the beam, respectively; c is the height of the neutralization axis.

The model developed by D'Ambrisi et al. [57] is suitable for calculating the flexural capacity of repaired timber beams reinforced with FRP bars. Orlando et al. [56] proposed another model which is suitable for timber beam balanced-reinforced with FRP sheet and the calculation method is simple yet produces accurate results. Other models were proposed based on different characteristics such as the height of the neutral axis and the mode of failure [59] and on the typical M-δ curve of timber beam under bending [60].

Different reinforcement positions of the FRP sheet and types of FRP have different effects. Wu et al. [73] conducted four-point bending tests on reinforced timber beams with cracks by attaching CFRP sheets in different positions; obtained results showed that the using CFRP sheet along the axial direction on the tensile side of timber beams produced better performance than using CFRP sheet on both sides of timber beams. Chun et al. [74] used hybrid fibers made of CFRP and AFRP to enhance the flexural properties of rectangular timber beams. Timber beams were made of two different species (Chinese fir, pine) and were reinforced with different layers of hybrid fibres prior to testing under two loading types. They carefully observed failure modes, flexural bearing capacity, load-deflection curves and section strain distribution, and compared performance of reinforced *vs.* unreinforced specimens, they reported that the flexural bearing capacity and stiffness was increased by 18.1%–62.0% and 13%–21% for reinforced pine, and 7.7%–29.7% and 6%–10% for reinforced fir, respectively. Zuo et al. [75] used basalt fiber sheet and plate as reinforcement materials; they studied the effect of different reinforcement layers on glulam beams by three-point bending test. The results showed that basalt fiber polymer enhanced the flexural performance of ordinary glulam beams, and the ultimate flexural bearing capacity, flexural stiffness, and ductility coefficients increased by 20.88%–111.25%, 18.7%–27.6%, and 23.0%–74.3%, respectively. Gómez et al. [76] studied and compared the flexural properties of four types of FRP reinforced timber beams. Subhani et al. [77] used a CFRP sheet externally on the tensile side of the LVL beam to enhance the flexural bearing capacity. Two types of bond arrangements as Plans 1 and 2 (Fig. 14) were adopted to study the enhancement effect on the ductility, stiffness, and ultimate bearing capacity of the beam. The results showed that compared with the control beam, the ultimate bearing capacity, ductility, and stiffness of Plan 1 increased by 10%, 14%, and 4%, respectively, whereas Plan 2 orientation showed significantly better performance as the ultimate bearing capacity, ductility, and stiffness improved by 25%, 30%, and 20%.

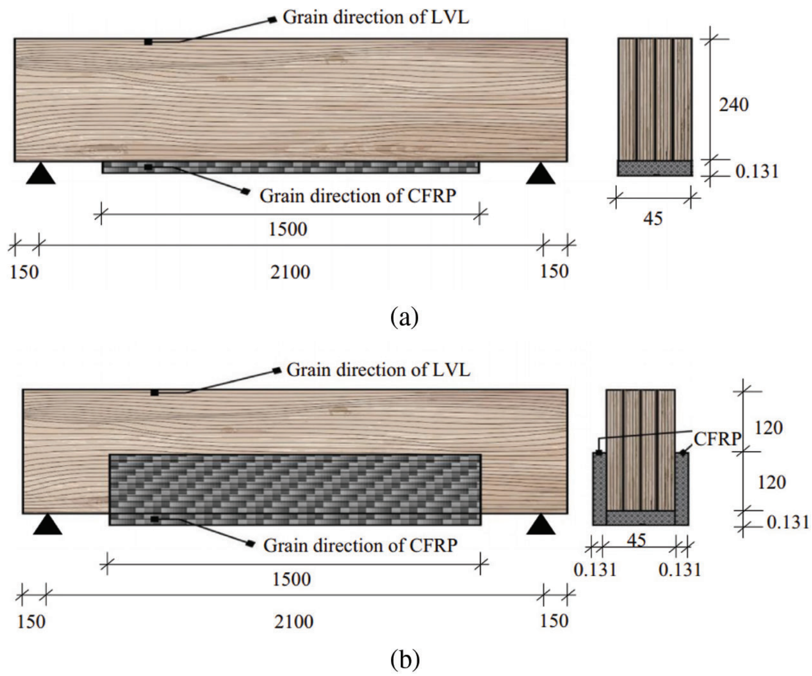


Figure 14: Elevation and cross-section of two strengthening plans [77]: (a) Plan 1; (b) Plan 2. All dimensions are in mm

Different loading methods produce different stress distributions. In addition to the three-point loading and four-point loading methods used in most experiments, Ouyang et al. [78] studied the influence of the modulus and thickness of FRP sheet, beam slenderness ratio and crack width on the bending deformation of the FRP sheet reinforced timber beams by using the method of free end concentrated load. The results showed that the free end deflection of FRP reinforced timber beams decreased with an increase in FRP thickness, elastic modulus, and shear modulus. The FRP sheet needs a larger load than the plate to be damaged for the same material and different forms of the sheet, and it is more economical.

The FRP sheets of the same material in different forms and timber beams with the same reinforcement material in different forms will also have different performance. Thorhallsson et al. [79] studied timber beams reinforced with relaxed basalt fiber, relaxed GFRP, prestressed basalt fiber, and uncemented timber beam. They found that the strength increased by 37%–57% when the beam was reinforced with basalt fiber or glass fiber, and the strength increased by 64% for the specimens with prestressed basalt fiber. Ouyang et al. [80] proposed the nonlinear governing equation for the second-order bending effect of beams and the expression for the critical load of simply supported beams reinforced with FRP. Valluzzi et al. [81] studied the beam reinforced with wet CFRP sheet attached to the lower surface and carefully investigated the connection characteristics between materials. They also conducted flexural tests on beams with or without CFRP. Yang et al. [82] analyzed the failure modes of simply supported beams with circular sections strengthened by the CFRP sheets, and established the governing equations for nonlinear small deflection. Zhou et al. [83] analyzed the effects of the FRP thickness, span depth ratio, reinforcement techniques, and joint types on the flexural performance of beams, and proposed failure prediction model. Bashandy et al. [84] used steel plate, GFRP sheet, and CFRP plate to strengthen the old and new timber cantilever beams and discussed the feasibility. They found that EBR was more effective when there was no visual requirement, and the ultimate load increased by 11%–22% with GFRP and 13%–34% with CFRP.

Many studies investigated the influence factors and performance of the FRP plate reinforcement for timber beams. Yang et al. [85,86] observed the failure modes and failure mechanisms of 18 FRP reinforced glulam beams, and also analyzed their ultimate load and flexural stiffness and compared with those of unreinforced beams. The test results showed that the enhanced glulam beam performed similar to the strengthened solid beam; the ultimate bearing capacity increased by 18%–63%, while the flexural stiffness increased by 32%–88%. When the reinforcement ratio was about 1.0%, the bearing capacity and stiffness of the FRP reinforced cypress glulam beam respectively improved by 1.82 and 1.35 times than common pine solid wood component, and the failure mode was mostly characterized by plastic compression failure. In addition, the mechanical model was analyzed, and an analytical solution of the deformation of the FRP-glulam beam was proposed.

Different configurations of the same FRP type has been reported to produce different performance. Li et al. [87] studied the influence of different configurations of FRP and synergistic reinforcement with bamboo composite on the bending properties of integrated timber. Eighteen integrated timber beams were adopted for the four-point bending test and the mid-span section strain was observed and recorded. The results showed that, compared with the unreinforced control group, the BFRP reinforced beams and the BFRP locally reinforced beams had no obvious effect on bending strength. The flexural strength of the beam reinforced by bamboo plate and the beam reinforced on tensile and compression sides was improved by 10.37% and 26.96%. Compared with the BFRP reinforced beams with the same reinforcement ratio, the utilization rate of FRP materials can be reduced by 33.3%. Corradi et al. [88] compared timber beams with and without CFRP reinforcement. The results showed that CFRP improved the flexural strength and tensile strength of the beams. Shekarchi et al. [89] evaluated bending properties of composite timber beams reinforced by flat plate, U-type and I-type GFRP. Fiorelli et al. [90] established a theoretical model for evaluating the flexural strength and stiffness of glulam beams with and without FRP reinforcement.

Based on available literature it is obvious that FRP sheet reinforced timber beams show good performance and has good potential in comparison to other reinforcing techniques. Most of the studies in the related field mainly focus on the effect of the FRP sheet types, number of layers, and reinforcement methods on the stiffness and bearing capacity of timber beams. A number of researchers proposed some analytical models to predict the observed behaviour. However, most of them focus on simply supported beams, and there are few studies that focus on other beams such as cantilever beams. In addition, the effect of different wood species on the mechanical properties of the reinforced beams should be investigated. The reinforcement effects of different woods need to be further studied. The existing research mainly includes the effect of reinforcement on flexural bearing capacity and stiffness, the influence of configuration and reinforcement method on mechanical properties, and further comparison of FRP with various reinforcing materials and shapes are also required.

3.3 Timber Beams Reinforced with the FRP Shell

There are few studies on FRP shell reinforcement. Qi et al. [91] carried out three-point bending test to investigate bending properties and failure modes of a new type of GFRP-balsa timber composite beam made of glass fiber reinforced composite (GFRP) shell and balsa wood core (Fig. 15). The results showed, compared to paulownia wood flat beam, the bearing capacity and bending stiffness of the GFRP-paulownia composite beam were 17.4 and 12.8 times higher than Paulownia flat beam, and 4.1 and 1.7 times higher than the GFRP hollow pipe. It should be noted, that there are a lot of studies on strengthening concrete and steel structures with FRP shells than timber beams due to higher technical requirements and prone to delamination of the latter. Table 4 shows the summary of effect of FRP reinforced timber beams.

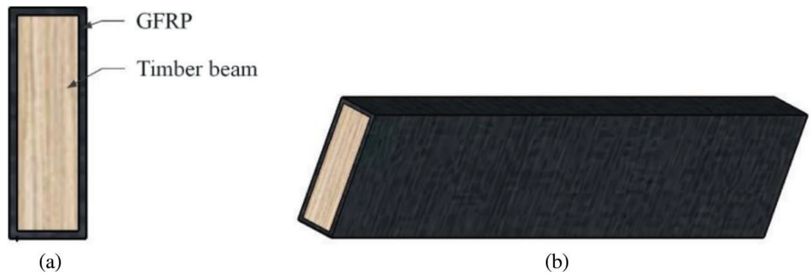


Figure 15: Reinforcement schematic diagram [91] (a is the sectional view, b is the longitudinal view)

Table 4: Summary of selected studies on bending performance of FRP-reinforced timber beams

Authors	The wood type	Reinforcing material	Loading method	Increase of the ultimate flexural bearing capacity	Increase of the flexural stiffness
Raftery et al. [58]	Low-grade glued laminated	GFRP plate	Four-point bending tests	31%	18%
Al-Hayek et al. [63]	Poplar in Xinjiang, China	Draped CFRP tendons	Three point bending tests	70%	10%
Andor et al. [70]	Norway spruce	CFRP	Four-point bending tests	30%	16%
Chun et al. [74]	Pine and fir	CFRP and AFRP	Four-point bending tests	18.1%–62.0% (pine) and 7.7%–29.7% (fir)	13%–21% (pine) and 6%–10% (fir)
Zuo et al. [75]	Glulam beams	BFRP (plate and sheet)	Three-point bending	20.88%–111.25%	18.7%–27.6%
Yang et al. [86]	Cypress	FRP	Three point bending tests	18%–63%	32%–88%
Li et al. [87]	European red pine, bamboo plate	BFRP	Four-point bending tests	10.37% (tensile side) 26.96% (compressive side)	–
Corradi et al. [88]	–	CFRP	Four-point bending tests	11.5% (trabecular beam) and 21.4% (girder)	–
Shekarchi et al. [89]	Beechwood	GFRP	Three-point bending tests	–	59%
Qi et al. [91]	Paulownia wood	GFRP	Three-point bending tests	17.4 times of the unreinforced pipe, and 4.1 times of the GFRP hollow pipe	12.8 times of the unreinforced pipe, and 1.7 times of the GFRP hollow pipe

3.4 Creep Resistance

The FRP reinforcement can reduce the creep deformation of timber beams. Creep in wood can be divided into two broad categories, i.e., elastic creep and mechanical adsorption creep [92]. The creep of bamboo and wood members is affected by temperature [93]. Based on experiments under constant temperature, Lu et al. [94] found that compared with unreinforced timber beams, the initial deformation of timber beams reinforced with FRP plates was reduced by 27%, and the relative creep deformation was reduced by 80%. Song et al. [95] carried out the creep analysis of FRP reinforced glulam beams and obtained the function of stress and cross-section strain of glulam beams changing with time under constant temperature and humidity. Kim et al. [96] established a three-dimensional finite element model for a load-displacement relationship, strain development, stress concentration, and failure mode of CFRP reinforced timber beams based on anisotropic wood constitutive relationship. Yahyaei-Moayyed et al. [97] strengthened southern yellow pine (SYP) and Douglas fir (DF) timber beams with AFRP. Based on the indoor creep experiment and adopting three clamps on three different loading samples at the same time, the authors determined the creep parameters of FRP and ordinary lumber and proposed a model to predict the creep response of FRP reinforcement beam. The results showed that the strength and stiffness of the AFRP reinforced beam improved, while the creep deformation reduced. The creep test equipment is shown in Fig. 16.

Figure 16: Creep test equipment [97]

Xu et al. [98] studied the experimental results of three timber beams (one unreinforced and two reinforced) under continuous load for 1200 days. The creep responses of the unreinforced beams were similar to those of the strengthened beams. The creep strain and curvature of the mid-span section of the strengthened beams were lower than those of the unreinforced beams. O'Ceallaigh et al. [99] used BFRP bars to strengthen timber beams. The control beams and the reinforced beams were placed for 75 weeks under the condition of the maximum compressive stress of 8 MPa. It was found that the total creep deflection of the BFRP bars was significantly smaller than that of the control beams.

In summary, studies on FRP creep properties were mainly carried out by applying long-term loads on the reinforced beams and control beams and measuring the strain generated by the test pieces. It was concluded that the FRP reinforcement can inhibit and delay the creep of timber beams and maintain the original mechanical properties of materials. Slow creep should also be ensured in a humid environment and under temperature fluctuations. When studying the creep properties, the applied force must keep the material in the elastic limit, so in further studies, it is necessary to consider higher requirements to load application and optimize the existing methods of load application to the material.

3.5 Prestressed Reinforcement

The mechanical properties of timber and other biomass materials can be better utilized by testing and improvement [100–105], the strength of FRP is far greater than that of timber beams, the strength of a loosely attached FRP cannot be fully utilized. To address this challenge, prestressing was applied to FRP sheets to improve the utilization of FRP strength.

Different prestress lead to different bending properties of beams. In order to reduce the impact of sliding failure on the performance, some studies adopted the method of simultaneous bonding and anchoring. Chen et al. [106] analyzed the effect of CFRP on bending performance under different prestressing conditions (Fig. 17). They found that when 50% prestressing was applied, the ultimate load increased by 15.8%, the bending strength increased by 38.5%, and the bending elastic modulus increased by 23.9% compared with those of unreinforced timber beams. When 58% prestress was applied, the ultimate load increased by 36.8%, the flexural strength increased by 63.8%, and the flexural modulus increased by 57.2% compared with those of the unreinforced beams. When 66% prestress was applied, the ultimate load increased by 51.8%, the flexural strength increased by 81.7%, and the flexural elastic modulus increased by 70.5%. Within the specified range, higher prestress of CFRP produced better the bending characteristics for timber beams under consideration.

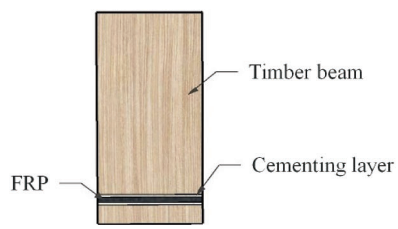


Figure 17: Schematic diagram of reinforcement section [106]

Prestressed FRP reinforced timber beams inevitably suffer prestress losses during processing, transportation, and use. Chen et al. [107] deduced and verified an initial prestress formula through experiments. Zheng et al. [108] established the prestress loss formula of FRP reinforced glulam beams based on the assumption of plane section and the relationship between force balance and deformation coordination. Brunner et al. [109] used gradient anchorage technology, prestressing FRP was applied from the center of the beam in stages, and the prestressed laminate was bonded to the timber beam with an electronic control device, which solved the problem of its easy delamination.

In conclusion, prestress improves the performance of FRP reinforcement. The degree of improvement is related to the magnitude of prestressing, the prestress application method, and the degree of prestress loss. Due to the material properties of the FRP reinforced beam, sliding failure is relatively easy to occur compared with traditional concrete structure. It can be solved by a combination of gluing and anchoring, stage reinforcement, and so on. Further research is needed to optimize the FRP reinforcement by applying prestress and reducing slip damage.

4 Shear Behavior of FRP Reinforced Timber Beams

Wood is an orthotropic material, the mechanical properties of which depend on the grain orientation of the flexural member. Under bending load, when the ultimate stress is exceeded, the wood shows shear failure due to the limited shear strength between layers parallel to the longitudinal axis of the grain [110].

The shear and withdrawal resistance of timber have been studied increasingly [111,112]. The existing studies on the shear behavior of timber beams strengthened by FRP plates focus on the bond shear stress, and the main failure mode was the debonding of FRP plates and adhesives or adhesives and timber beams. Yang et al. [113] deduced three common loads such as a uniformly distributed load, a concentrated load, two symmetrical concentrated loads, as well as calculation formula for the component interface bonding shear stress, and main influencing factors such as the elastic modulus ratio of FRP and glulam, FRP reinforcement ratio, the relative height of the ramen veneer, and the rubber thickness at the bonding interface. Vahedian et al. [114] carried out tests on 136 FRP reinforced timber and established a new prediction model for calculating interfacial strain distribution, slip distribution, and shear stress.

According to the studies on FRP reinforced timber beams, the failure mode was mostly characterized by the shear failure between parallel layers along the longitudinal axis of the wood grain. Chun et al. [115] carried out the shear tests of 12 beams, which showed that the shear strength of timber beams reinforced with carbon-aramid hybrid fiber sheet increased by 6.9%–109.6% (pine) and 11.9%–103.6% (fir) compared to unreinforced timber beams. Xu et al. [116] found that in bending and shearing zone, the bearing capacity of timber beams reinforced with CFRP fabric increased by 28.4% on average, while failure displacement increased by 32.8% on average. Ling et al. [117] found that the shear strengthening effect of CFRP is generally higher than that of GFRP, and the shear capacity of single-layer and double-layer timber beams strengthened by longitudinal unidirectional CFRP increased by 32.9% and 68.6%, respectively. Ribeiro et al. [118] found that the shear stress at the center was less than the theoretical value. FRP reinforcement can effectively enhance the shear strength of timber beams and the reinforcement effect depends on the property of FRP itself, the amount of FRP, and the reinforcement method.

In conclusion, the use of FRP reinforcement helps to improve the shear bearing capacity of timber beams and reduce sliding failure. The main factors influencing the reinforcement are the elastic modulus ratio of FRP and glulam, FRP reinforcement ratio, the relative height of the ramen veneer, and the rubber thickness at the bonding interface, types and forms of FRP, reinforcement method and so on. There are few studies on the shear behavior of FRP reinforced timber beams, and further research on other reinforcement methods that can improve the shear behavior of timber members is still necessary.

5 Conclusion

This paper summarizes the bonding methods and bond-slip models of FRP and timber beams, the flexural and shear properties of FRP reinforced timber beams, analyzes the influencing factors, and discusses the problems that need to be solved for each reinforcement method. As an environmentally friendly and renewable resource, wood plays an increasingly important role in the field of construction. FRP has been paid more and more attention in the construction industry because of its obvious advantages such as corrosion resistance, sustainability and low density, which cannot be replaced by steel. There are still some important problems in the study of FRP timber beams that need to be further investigated and solved:

(1) To increase the bonding strength and improve the performance of FRP and timber beams, the properties of binders, bonding steps, and the contact between the FRP bars and timber beams need to be further analyzed and optimized.
(2) The comparison of different types and shapes of FRP, as well as beams (such as cantilever beams), under the same conditions should be further investigated. The FRP shell reinforcement of timber beams calls for further study as well.
(3) There are few studies on the influencing factors of the shear performance and reinforcement effect of FRP beams.
(4) Since reinforcement ratio and reinforcement method affect the performance of timber beams reinforced with prestressed FRP, the prestress application method needs to be further studied and optimized.

(5) In addition, it is necessary to increase the durability and fire resistance of FRP reinforced timber beams and improve the production technology in order to reduce the cost of producing materials while ensuring quality.

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Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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