Prestressed Wood or Bamboo Structures: Historical Overview and State-of-the-Art

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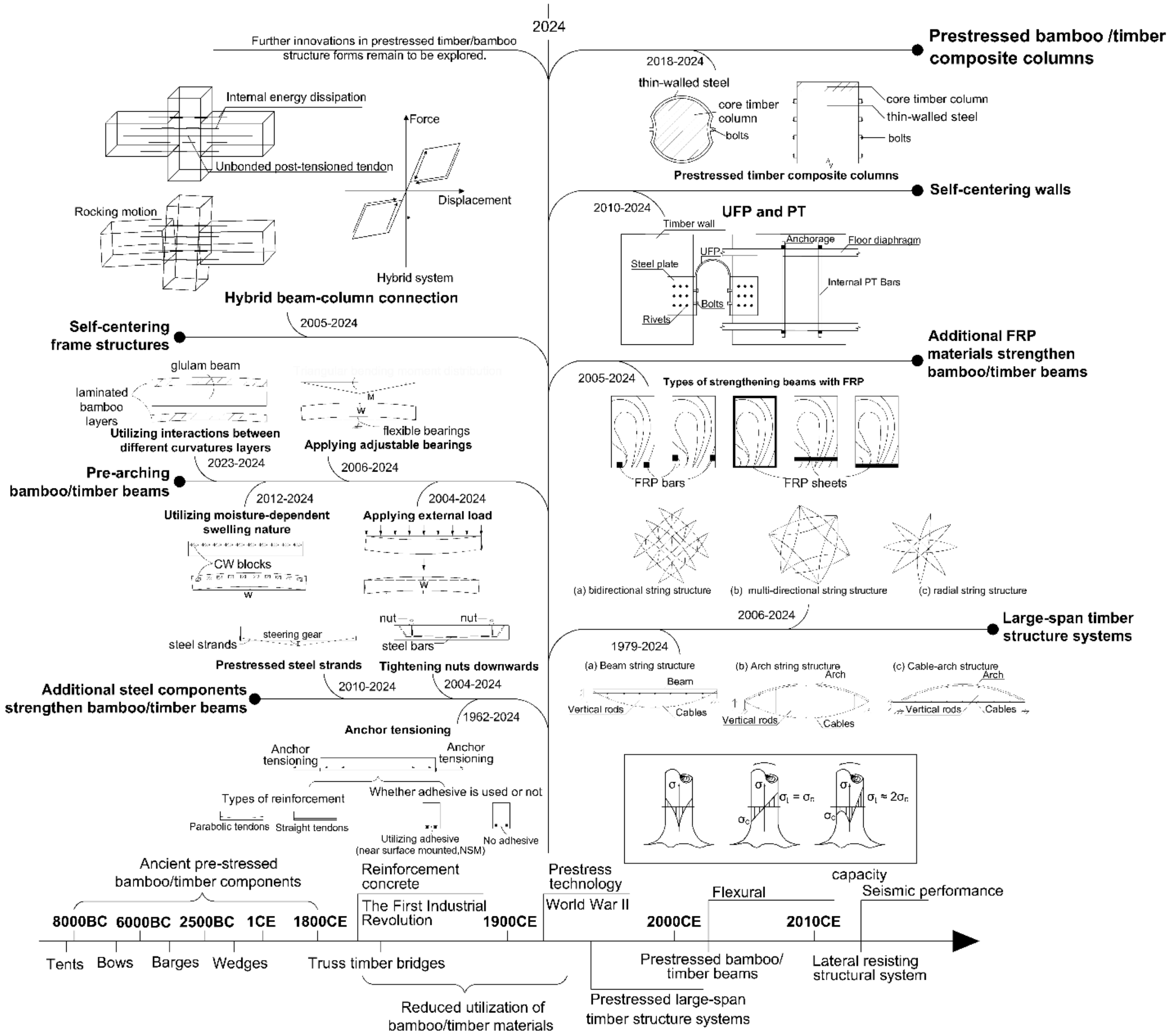
GRAPHICAL ABSTRACT



Prestressed Wood or Bamboo Structures: Historical Overview and State-of-the-Art

Qingfang Lv, Juewen Wang, and Yujie Lu *

This review explores the evolution of prestressed timber/bamboo structures across component, connection, and structural levels, and it examines the corresponding performance of prestressed specimens. Firstly, the utilization of prestress in beams is achieved through either pre-bending methods or the incorporation of additional components. Subsequently, prestress in timber/bamboo columns often appears in the form of lateral confinement, which improves the compressive performance of the columns. On the structural level, prestress is applied in self-centering structural systems and large-span string timber/bamboo structures. Detailed schematic diagrams illustrate the application methods and underlying principles of prestress in timber/bamboo components and structures. Based on the current state of research, the future research needs and development directions are outlined. The research aims to promote the broader application of prestressed timber/bamboo structures in practical engineering, contributing to the advancement of sustainable building practices.

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Keywords: Timber/Bamboo structures; Prestress; Beams; Columns; Self-centering systems; String structures

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INTRODUCTION

Timber/bamboo structures, as an ancient architectural form, have played an essential role in construction since primitive societies and continue to exert influence to this day. The 67-meter Yingxian Wooden Pagoda, completed in 1056, has been preserved for thousands of years and has served as a representative example of ancient timber construction techniques (Liu and Yang 2019). The Forbidden City in Beijing, one of the most emblematic collections of ancient timber structures, employed exquisite mortise, tenon joints, and bracketing systems (Paliszewska-Mojsiuk 2018). This configuration ingeniously alleviated impacts caused by earthquakes, thereby ensuring the structure's stability and safety (Gustafson *et al*. 2008). In the 1840s, Chicago, USA, witnessed the emergence of lightweight timber frame houses constructed using 38 mm thick timber, assembled with long nails (De Geetere and Ingelaere 2014). This lightweight timber frame structure has progressively become one of the most predominant architectural forms for low-rise housing, dormitories, and hotels (Caniato *et al*. 2017). The Dai's bamboo house in China represents a typical example of traditional bamboo architecture. The connection method involves the tying of bamboo rafters, characterized by the use of local materials, effective ventilation and moisture prevention, and high spatial efficiency (Sattar. 1995). In contrast, the Naman Conference Center in Da Nang, Vietnam, integrates bamboo with modern materials including glass and steel, offering new solutions to current environmental challenges (Thi *et al*. 2017).

In the latter half of the 19th century, the demand for large-scale infrastructure facilitated the emergence and utilization of steel and reinforced concrete (Yeoh *et al*. 2011). Due to the limited industrial technological capabilities of timber/bamboo structures at that time, they gradually receded from the purview of construction engineering (Omenzetter *et al*. 2011). Nevertheless, since 1950, timber/bamboo materials have experienced a resurgence in construction practices (Aloisio *et al*. 2023b). The use of bamboo in foundations, doors, windows, and walls has progressively increased, enabling nearly all parts of a house, to be constructed using bamboo except fireplaces and chimneys (McClure 1956). The distribution of timber architecture in England was summarized by Smith (1965), highlighting the distinctions and connections among different regional forms of timber structures. Timber planks can be widely applied in farm buildings such as sheds, barns, silos, and granaries (Banks 1972). Timber arch bridges and timber truss bridges also became increasingly common starting from the 1980s (Duwadi and Ritter 1997; Totman 1983; Verna *et al*. 1984). The reasons for this revival can be attributed to the following two aspects:

(1) The rise of the green and sustainable development concept

In recent years, the green and sustainable development concept has prompted a reassessment of traditional materials' environmental impact in construction engineering (Abdulhameed *et al*. 2023). Studies on timber/bamboo materials have shown that they are associated with low carbon emissions and energy consumption during growth and processing (Lim *et al*. 2023). Additionally, buildings with timber/bamboo materials exhibit excellent insulation properties, resulting in outstanding lifecycle carbon emissions and energy utilization efficiency (Dodoo *et al*. 2014; Robati and Oldfield 2022). These advantages have driven the application of timber/bamboo structures in green buildings.

(2) Development of modern bio-materials

Natural wood is susceptible to decay, with irregular shapes and varying mechanical properties. Its mechanical performance is significantly impacted by environmental factors such as temperature and humidity, making it unsuitable for use in some aspects of construction (Bartlett *et al*. 2019; Cui *et al*. 2024). Against this background, engineered timber/bamboo materials have gradually emerged, such as glulam-laminated timber (*GLT*), cross-laminated timber (*CLT*), and laminated veneer lumber (*LVL*). *GLT*, which dates back to 1870, involves bonding solid timber sections together in the same direction through gluing (Kim *et al*. 2011). Each layer of timber in *CLT* is glued perpendicularly to the adjacent layers, providing uniform strength in both directions (Huang *et al*. 2022; Bai *et al*. 2024). *LVL* is a single-layer board with the grain oriented in the same direction, which has a better mechanical performance than common *GLT* (Zhu *et al*. 2007; (Ardalany *et al*. 2011). Given the scarcity of timber and the abundance of bamboo resources in some areas, various engineered bamboo materials, such as glulam-laminated bamboo (*GLB*), cross-laminated bamboo (*CLB*), and laminated veneer bamboo (*LVB*), have been proposed (Lee *et al*. 1998; Liu *et al*. 2016; Chen *et al*. 2022). Due to the superior mechanical properties of bamboo fibers, engineered bamboo materials manufactured from them exhibit higher density, elasticity, and strength compared to timber (Chen *et al*. 2022; Tian *et al*. 2023), and the bending strength of *GLB* is higher than that of *CLB* (Sinha *et al.* 2014).

Although engineered timber/bamboo materials are economical and practical, effectively addressing the defects of natural wood, the promotion of timber/bamboo structures still faces challenges. Firstly, the fire resistance of bamboo and timber is directly related to the safety of occupants in buildings. Published research has employed the charring rate to measure the fire resistance of timber/bamboo materials (Schmid *et al*. 2014; Xu *et al*. 2015; Zhang *et al*. 2019). Based on the Reduced Cross Section Method (*RCSM*), novel fire design models for glulam timber/bamboo have been proposed to provide significant references for modern bamboo and timber engineering (Xu *et al*. 2018; Cui *et al*. 2023).

Furthermore, compared with steel or concrete materials, the relatively lower mechanical performance and brittle failure mode of timber/bamboo materials limit the development of timber/bamboo structures towards long spans, high-rise, and large-scale applications (Li *et al*. 2019; G. Wang *et al*. 2024). Existing research has explored additional components, such as *FRP* plates (Canning and Luke 2008; Colombi and Fava 2015; Stratford and Cadei 2006), strips (Motavalli *et al*. 2010; Khedmatgozar Dolati and Mehrabi 2022), bars (Cheng *et al*. 2018; Hadhood *et al*. 2021; Wdowiak-Postulak *et al*. 2023), or steel strands (Ranzi and Ostinelli 2017; Zhang *et al*. 2022) for reinforcing timber/bamboo elements, but their combined efficiency still requires improvement.

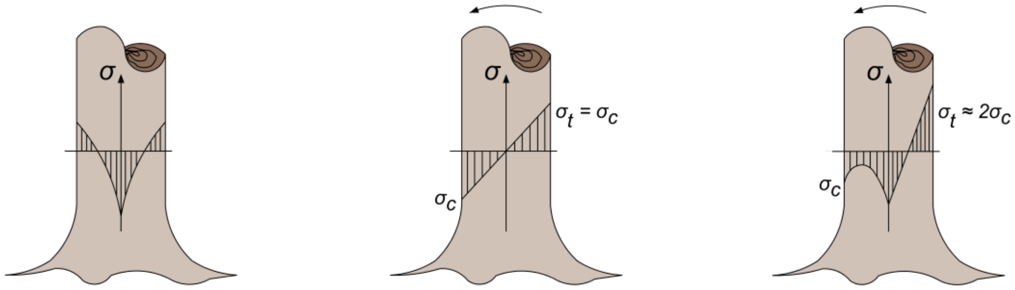
Additionally, despite the high strength-to-weight ratio of timber/bamboo materials, which offer higher utilization efficiency compared to low-carbon steel and ordinary concrete (Crocetti 2016), many experimental investigations have shown that failures in timber/bamboo structures are mainly concentrated in the connection areas. The connection methods, joint stiffness, and bearing capacity directly impact the overall performance of prefabricated timber/bamboo structures. Although many new modern connection methods have been proposed, such as nail connections (Gattesco and Boem 2016; Ruan *et al*. 2022), screw connections (Hossain *et al*. 2016; Schiro *et al*. 2018), bolted connections (Lam *et al*. 2010; Quenneville and Mohammad 2000; Song *et al*. 2017; Cui *et al*. 2024), and self-tapping wood screws (Li *et al.* 2017; Petrycki *et al*. 2020; Cui *et al.* 2022), the most suitable connection for improving the brittle characteristics of timber/bamboo structures still needs to be studied.

To solve the issues mentioned above, prestress technology, which has served as a main reinforcement approach for concrete structures (Akl *et al*. 2017; Gao *et al*. 2017), is introduced into timber/bamboo structures for the enhancement of structural components. The introduction of prestress can significantly enhance the fire resistance of glulam timber or bamboo, with the degree of enhancement positively correlated with the magnitude of prestress (Quiquero *et al*. 2020; Zhang *et al*. 2024). In the research on mechanical properties, extended research has demonstrated the effectiveness of prestress in improving strength and stiffness, reducing deflection, and optimizing tress distribution. Additionally, prestress technology is also utilized in the connections of timber /bamboo structures to improve overall stress and deformation patterns, enhancing the vertical load-bearing and seismic performance of structures. This advancement promotes the development of large-span and high-rise buildings.

This study provides an overview of the methods for applying prestressing technology in timber/bamboo structures at the component, connection, and structural levels and the corresponding performance of the prestressed specimens. By summarizing the characteristics of existing research, this paper identifies the directions to be explored, particularly in the lack of research on efficient reinforcement for timber/bamboo materials, unestablished prestress loss standards, and the actual seismic performance. This review points out future research directions, providing theoretical references for engineering applications.

THE ORIGIN OF PRESTRESS IN TIMBER/BAMBOO STRUCTURES

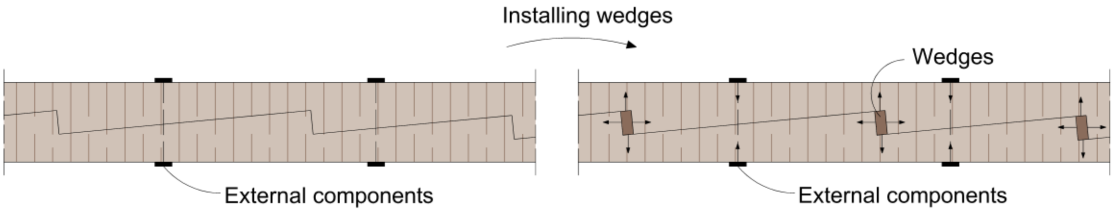
A prestress condition exists early in the growth process of trees. The stress associated with the expansion of cross-sections during germination is referred to as growth stress. The causes and distribution characteristics of growth stress in trees were first discussed by Münch (1938) and Jacobs (1938). Growth stress was observed to be unevenly distributed radially along the cross-section, with compressive prestress generated at the center and tensile prestress at the outmost edges, as shown in Fig. 1(a). Due to the susceptibility of buckling under compression for wood fibers (Boyd 1950), the compressive strength along the grain is typically only about half of its tensile strength. Commonly, wind or seismic loads result in a bending response in trees, causing tension on one side and compression on the other side of the cross-section, as illustrated in Fig. 1(b). After the superimposition of growth and bending stress states, compressive stress on the compression side is mitigated while tensile stress on the tension side increases, as illustrated in Fig. 1(c). The utilization of the mechanical properties and overall load-bearing capacity are improved.



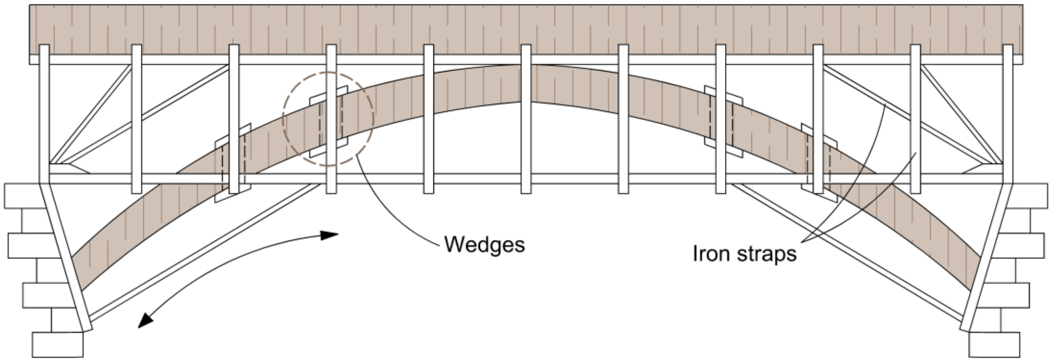
(a) Growth stresses **(b)** Bending stresses **(c)** Resulting stresses

Fig. 1. Longitudinal stresses in a tree trunk, redrawn from the description of Sehlström (2021)

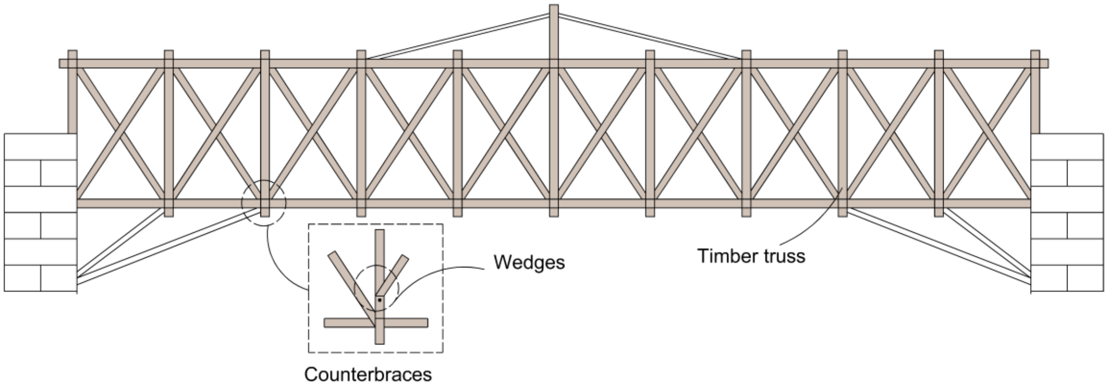
In ancient times, tents constructed with tensioned bent slender branches to resist wind loads exemplified an early application of prestress in timber/bamboo structures (Gasparini 2006). Wedge connection was a significant traditional structure connection form (Gustafson *et al*. 2008). A wedge was a small wooden peg with a thick top and sharp bottom. Its tip was inserted into a gap in the connection, and the flat end was struck with a heavy object driving the wedge deeper (Yang *et al*. 1999), as shown in Fig. 2(a). The gaps expanded and prestressed to achieve fixing and connection. Grubenman combined wedges with iron straps to construct the first laminated timber arch (James 2017). The Wettingen Bridge, built in 1765, was based on this principle, as shown in Fig. 2(b) (Caldenby 2018). The basic wedges were improved by incorporating iron straps, with additional tensile strength and stability added to the bridge.



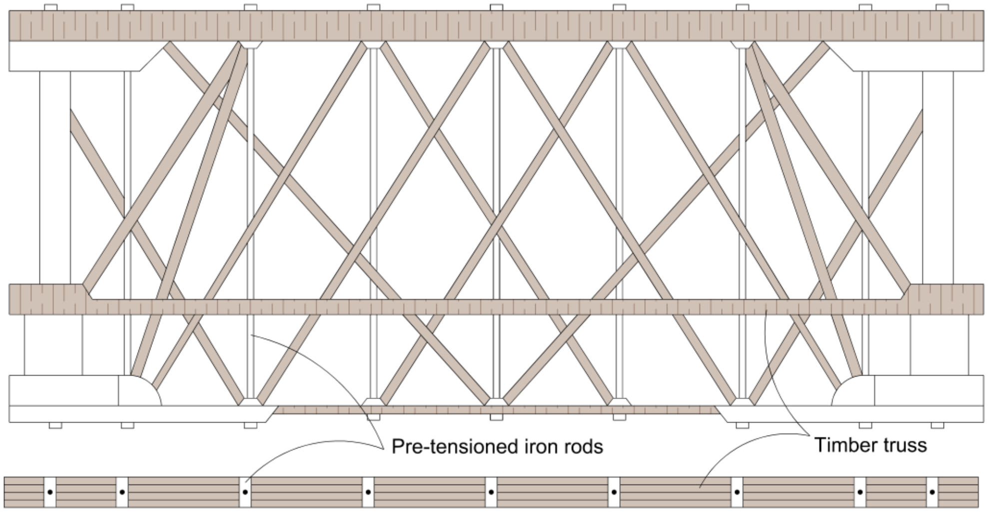
(a) Wedges principle, redrawn from the description of Yang *et a*l. (1999)



(b) Wettingen bridge, redrawn from the description of Caldenby (2018)



(c) Lon's patent, redrawn from the patent of Long (1830)



(d) Howe's patent, redrawn (Howe 1840)

Fig. 2. Evolution of prestressed timber bridges

In the 19th century, the rapid expansion of American railroads drove the further development of prestressed timber bridges (Wipf *et al*. 2000). It began with Lon's patent for a timber truss bridge (Long 1830), as shown in Fig. 2(c), where counterbraces applied prestress using wedges (Gasparini and Simmons 1997a,b; Gasparini 2006; Gasparini *et al*. 2006). This method incorporated engineering mathematical principles to distribute loads and stresses within the structure better. However, it was soon superseded by Howe's new patent (Howe 1840), which introduced pre-tensioned iron tendons into the truss, as illustrated in Fig. 2(d) (Sutherland 2016). The introduction of iron tendons also facilitated the construction of more standardized and reliable bridges.

Timber/bamboo structures have gradually evolved into modern large-span structural systems represented by glued laminated timber structures (D'Aveni and D'Agata 2017; Li *et al*. 2019; Jia 2022). The development of prestress in timber/bamboo structures is exhibited in Fig. 3. The review of timber/bamboo structures in the following sections is divided into the following main sections in order from components to structures: (1) Prestressed timber/bamboo beams; (2) Prestressed timber/bamboo composite columns; (3) Timber/bamboo lateral resistance structural systems adopting prestress technology; and (4) Prestressed technology in large-span timber structural systems. The methods of prestress applied and the effects it contributed to in timber/bamboo components, connections, and structures are discussed in detail.

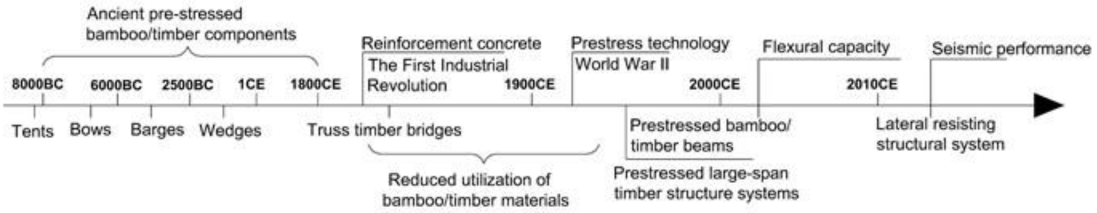


Fig. 3. Development of prestress in timber/bamboo structures

PRESTRESSED TIMBER/BAMBOO BEAMS

Applying Prestress through Pre-arching

The elastic modulus and strength of timber/bamboo materials are relatively lower compared with steel and concrete, making timber/bamboo beams prone to deformation and brittle bending failure (Zheng *et al*. 2021; Arafat and Imam 2022). Therefore, various prestressing techniques have been introduced to enhance the mechanical performance of timber/bamboo beams or other bending components. One common method is applying external loads to achieve pre-arching, as shown in Fig. 4(a). After flipping, the pre-arched timber beam experiences tension in the upper flange and compression in the lower flange, resulting in improved flexural load capacity (De Luca and Marano 2012).

In 2005, Borri *et al*. (2005) attained prestress in beams through the three-point bending test, with the stress intensity corresponding to about 25 to 35% of the ultimate timber flexure strength. The Preflex process was first implemented in prestressed concrete beams, applying symmetric four-point bending loads to achieve a more uniform stress distribution in flexural members. The Preflex cambering method for timber flexure members was proposed by Morano and Mannini (2006). In this method, the bottom of the beam was turned upwards before a two-point load was applied. The end anchors were tightened when the deformation of the *GLT* beam reached the predicted value and a pre-arched beam was achieved after rotating. Moreover, Lehmann (2015) and Negrão (2016) achieved beam cambering using an adjustable support that can move up and down, creating a triangular moment distribution in the beam, as shown in Fig. 4(b). However, due to the excessive support force and bearing displacement required, it was not suitable for large-size beams.

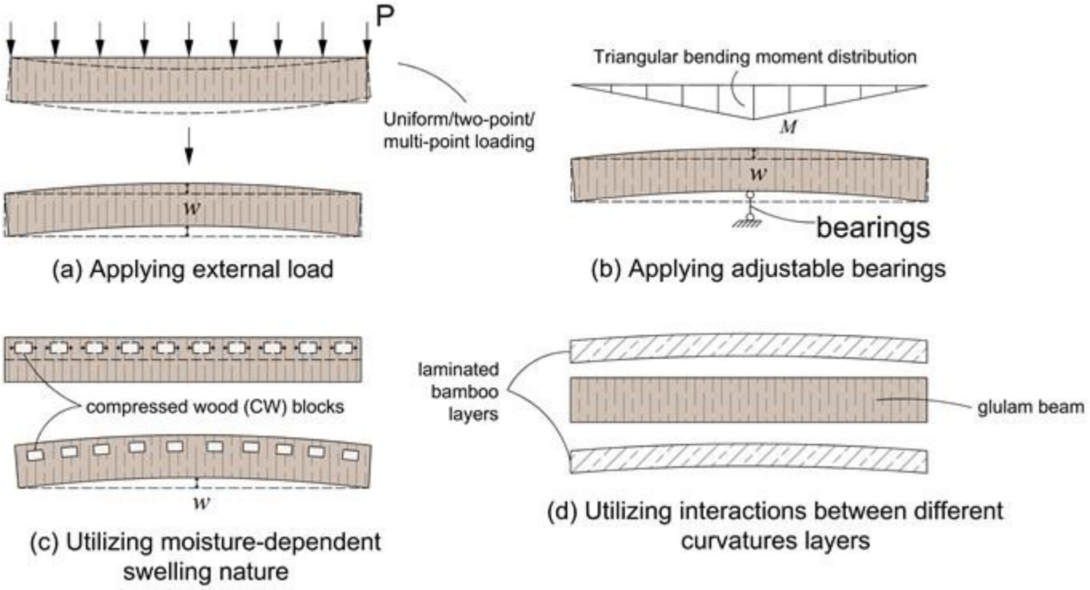


Fig. 4. Main forms of pre-arched timber/bamboo beams

Anshari and associates (Anshari *et al*. 2012; Anshari and Guan 2014; Anshari 2015) conducted a series of research on inducing camber in timber beams using the moisture-dependent swelling nature of compressed wooden (*CW*) blocks since 2012. The researchers cut rectangular holes at the top of *GLT* beams and inserted *CW* blocks with low moisture content to induce camber through hygroscopic swelling, as shown in Fig. 4(c). Significant initial tensile stress at the top and compressive stress at the bottom of the beam was generated. Compared with non-prestressed beams, beams with three 45mm *CW* blocks had flexural stiffness increased by 19% and the load-bearing capacity increased by 14%. In 2017, Anshari and Guan (2017) further validated the effects of the thickness and depth of *CW* blocks on initial flexural stiffness and the ultimate load-bearing capacity of beams through finite element analysis. The results illustrated that increasing the thickness and insertion depth of *CW* blocks could enhance the initial flexural stiffness of the beam by an average of 20%, but the improvement in ultimate flexural load capacity was relatively limited. Müller and associates (Müller 2020; Müller *et al*. 2021) applied Anshari's method to timber-concrete composite components to reduce the buckling of timber elements caused by cast-in-place concrete.

In 2023, Zhang *et al*. (2023) presented a pioneering concept that utilized the laminated interaction between layered timber/bamboo components with different curvatures to generate prestress, as shown in Fig. 4(d). A single layer of bamboo was glued and bent in a curved arc-shaped mold and then bonded with a straight glulam beam to form a composite component. In this process, the pre-bent laminated bamboo layer was straightened, and prestress was stored within it. The study found that compared with non-prestressed beams, the bending performance of sandwich beams with top and bottom laminated bamboo layers was obviously improved, showing a shift in failure mode from brittle tensile to ductile failure.

Applying Prestress through Additional Components

In addition to the aforementioned cambering methods, using additional prestressed components to reinforce timber/bamboo beams is also a widely cited effective method (Garas and Chalmers 1980; Gessner *et al*. 2019). The forms of additional prestressed components include prestressed steel bars (Chen *et al*. 1998; De Luca and Marano 2012), steel strands (Guo *et al*. 2021; Zhang *et al*. 2022), *FRP* materials (Achintha and Balan 2019; Breveglieri and Czaderski 2021; Custódio and Cabral-Fonseca 2023), *etc*. The methods of combining prestressed components with main load-bearing beams include internal unbonded or bonded methods (Al-Emrani and Kliger 2006; Capozucca 1998; Yi *et al*. 2015), and the Near Surface Mounted (NSM) method (Al-Saadi *et al*. 2017; Rocha *et al*. 2023), *etc*.

Post-tensioned steel bars or wires

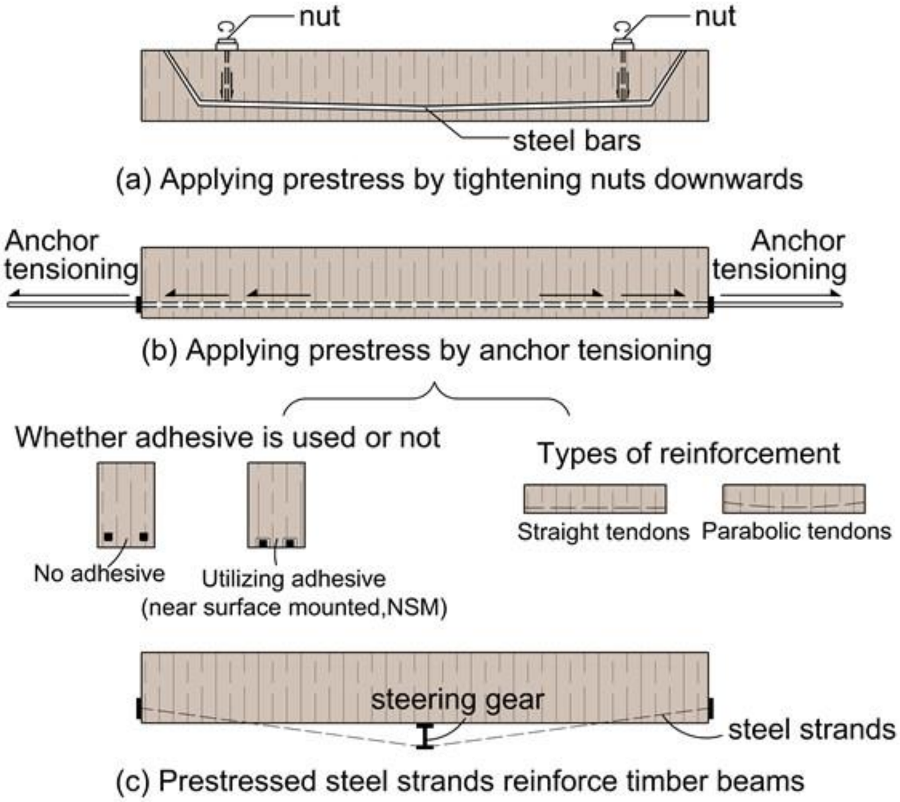


Fig. 5. Post-tensioned steel bars or wires strengthen bamboo/timber beams

In 1962, Bohannan first proposed the idea of using prestressed high-strength steel bars or strands in timber/bamboo structures to improve mechanical performance. Peterson (1965) used epoxy resin to bond prestressed steel bars on the tension side of timber beams in 1965. Song *et al*. (2002) drilled holes at the end of timber beams and placed 4 mm diameter round steel bars at the bottom edge, then applied prestress by tightening nuts, as shown in Fig. 5(a). De Luca and Marano (2012) used mechanical tensioning devices to apply a pre-tension force of 18 kN to steel bars, then bonded the bars with adhesive into the bottom grooves of beams as external prestress reinforcement, as shown in Fig. 5(b). The stiffness and ultimate load capacity of the beams increased by 37.9% and 40.2% respectively, and the ductility increased by 79.1% compared to unreinforced components.

Negrão *et al*. (2016) discussed the effects of pre-tensioning and post-tensioning methods on beams reinforced with prestressed bars. The adhesive was required in the pre-tensioning method, while the steel bars were anchored at the beam ends using mechanical devices before applying prestress in the post-tensioning method. The long-term fatigue risk of the adhesive interface in the pre-tensioning method made post-tensioned bars more suitable for practical engineering applications. Liu *et al*. (2008) discovered that setting post-tensioned bars in the tension section improved the ultimate load capacity significantly, whereas the improvement in stiffness was imitated. Wei *et al*. (2020) and Tian *et al*. (2021, 2023) found that embedding post-tensioned steel bars in bamboo beams enhanced stiffness, load-bearing capacity, and material efficiency. However, the influence of prestress level on ultimate load capacity was limited under the same reinforcement ratio.

The selection of bonded and unbonded prestressed tendons directly affects the overall performance of flexural members. Bonded prestressed tendons form an integral whole with beams by using adhesive (Al-Emrani and Kliger 2006; Hahn *et al*. 2019), while unbonded prestressed tendons transmit prestress directly through end anchorage, avoiding potential negative impacts from the adhesive (Bedriñana *et al*. 2021; Bu and Wu 2018). McConnel *et al*. (2014) studied the flexural performance of bonded and unbonded linear prestressed glulam beams, finding that unbonded prestressed timber beams contributed to a 17.6% and 8.1% rise in load-bearing capacity and stiffness respectively. Meanwhile, bonded prestressed increased about 40.1% in load-bearing capacity and 30.0% in stiffness, showing a more significant improvement in beam performance. Christoforo *et al*. (2022) conducted similar experiments, finding that failure mode changed from tension fiber rupture to compression fiber buckling and wrinkling.

Steel strands possess higher tensile strength compared to steel bars, and they are also widely used in the external prestress reinforcement of bending components, as shown in Fig. 5(c). Yang *et al*. (2016) applied prestress to steel strands using a jack. The *GLT* beams reinforced with externally prestressed steel strands showed significant improvements in ultimate load-bearing capacity and flexural stiffness. Prestressed steel strands also changed the brittle tensile failure mode into ductile compressive yielding failure mode. Guo *et al*. (2018) studied the short-term and long-term bending deflections of bamboo-timber composite beams reinforced with prestressed steel strands. Under the same external load level, prestress could reduce costs effectively by saving 13.3% to 52.0% on bamboo-timber composite materials. Additionally, the application of prestress effectively reduced the long-term deflection of composite beams. Zhang *et al*. (2022) proposed a new steel-bamboo composite beam strengthened with externally prestressed steel strands tensioned by cross-core jacks. Test results indicated that two-point prestressed specimens exhibited better deformation performance and higher loading-bearing capacity than the one-point prestressed specimens.

FRP materials

Fiber Reinforced Polymer (*FRP*) materials, characterized by high strength, good ductility, lightweight, and corrosion resistance, have been widely used in the reinforcement of building structures. With successful applications of prestressed *FRP* materials in concrete, attempts have been made to reinforce timber/bamboo structures with *FRP* materials. The common reinforcement practice was achieved by gluing (usually epoxy resin) sheets, plates, bars, *etc*., to timber beams.

According to the bonding position, *FRP* reinforcement of bamboo-timber beams can be categorized into five forms, as shown in Fig. 6. The method (a) in Fig. 6 directly performs *in-situ* flexural reinforcement (Johnsson *et al*. 2007), which is relatively convenient for construction. Based on method (a), *FRP* can also be fixed inside the beam, and this modified method (b) in Fig. 6 can be directly incorporated into the production process of glued-laminated timber. Method (c) utilizes thin *FRP* sheets to wrap the entire timber beam, allowing reinforcement in cases of partial timber degradation and cracking. In methods (d) and (e), the bottom of the timber beam is slotted and *FRP* bars are inserted.

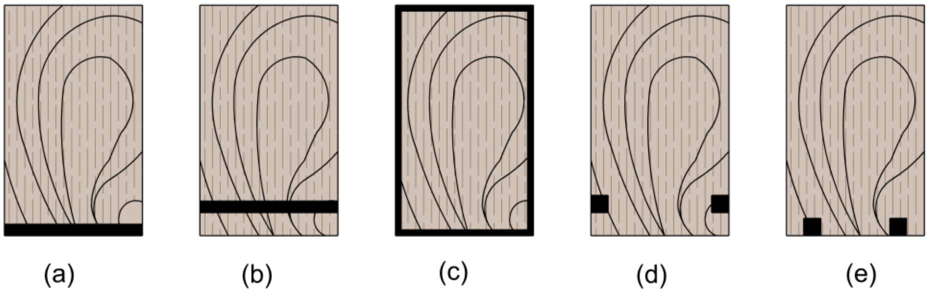


Fig. 6. Types of strengthening beams with *FRP*

Numerous studies have employed pre-tensioned *FRP* bars to reinforce timber/bamboo components. Johnsson *et al*. (2007) adhered carbon fiber reinforced polymer (*CFRP*) bars to the bottom grooves of beams with epoxy adhesive, validating the Near Surface Mounted (NSM) method for timber components. Ahmad (2010) applied prestress to *GFRP* bars by mechanical tensioning. The bending performance of timber beams reinforced with bonded glass fiber (*GFRP*) bars was studied, showing enhancements in both load-bearing capacity and stiffness after reinforcement. Lv *et al*. (2019) proposed a one-step forming method suitable for large-scale factory production to produce prestressed bamboo beam specimens. The one-step forming method combined pre-tensioned basalt fiber-reinforced polymer (*BFRP*) bars with bamboo through compression molding. The *BFRP*-bamboo composite beams exhibited better flexural performance. Wdowiak-Postulak and associates (Wdowiak-Postulak 2023; Wdowiak-Postulak *et al*. 2023, 2024) conducted four-point bending tests on timber beams enhanced by different post-tensioned bars, including steel, glass, and basalt bars. The results indicated that prestressed steel bars provided the most significant improvements in ultimate strength and stiffness.

In terms of *FRP* sheets or plates, researchers mainly have adopted three methods to apply prestress in timber/bamboo structures (Halicka and Slosarz 2021, 2022). The first method involved adhering *FRP* sheets to the bottom surface after cambering the beam. Triantafillou and Deskovic (1992) first established the method of *FRP*-sheet reinforcement for timber/bamboo structures. *CFRP* sheets were adhered to the tension surface of the timber beam. Wang *et al*. (2016) also conducted similar experiments, proposing that this method was suitable for reinforcing traditional timber structure beams. Borri *et al*. (2005) adhered *CFRP* sheets to the bottom surface of timber beams after the pre-bending process with three-point loading. It was observed that three layers of *CFRP* sheets could enhance the flexural capacity by 60.3% compared with unreinforced beams.

In the second method, the strips were pre-tensioned and then adhered to the bottom surface of the beam with adhesive. Dolan *et al*. (2001, 2016) used hydraulic jacks to introduce kevlar fiber-reinforced polymer (K*FRP*) fabric and *GFRP* rods to reinforce *GLT* beams. It was observed that the stiffness increased by 25% and 70%, and the ultimate flexural strength increased by 25% and 110%, respectively. İşleyen *et al*. (2021, 2023) conducted analyses of pre-tensioned *CFRP*-reinforced timber beams, finding that the flexural performance of damaged timber beams could be restored to an undamaged state after reinforcement. Halicka and Slosarz (2021, 2022) used hydraulic actuators to tension *FRP* sheets, which were then adhered to the surface of timber beams. The advantages of pre-tensioned *CFRP* strips lie in reducing beam deflection and shifting the failure mode from flexural failure to delamination failure.

Step-wise pre-stressing was the third method. This method was first proposed by Stöcklin and Meier (2003) and was initially applied to prestressing concrete structures at EMPA (Swiss Federal Laboratories for Material Testing and Research). In this method, a pre-tensioned section was bonded in the middle of the *FRP* strip at mid-span first. An electric heating system was used to accelerate the curing of the adhesive. After the middle part of the *FRP* strips was firmly bonded to the mid-span of the beam, the prestress value was reduced and the *FRP* was adhered to both sides of the beam gradually. These steps were repeated multiple times until the entire strip was bonded. Brunner and Schnüriger (2005) used the step-wise pre-stressing method to introduce prestress to *FRP* plates reinforcing timber beams. Epoxy adhesive is applied to one side of the *FRP* plate, and heating activates the adhesive in that area, attaching the *FRP* to the bottom mid-span of the beam. Starting from the mid-span, the process gradually moves towards the supports while reducing the prestress. Dagher and Altimore (2005) suggested that the load-bearing capacity of prestressed *GFRP* reinforced timber beams using the EPMA method increased by about 95% compared with non-reinforced beams.

Prestress Loss

Prestress loss is inevitable in prestressed flexural members. The loss can be classified into immediate losses and long-term losses based on the time the losses occurred. Immediate loss includes friction loss, anchorage loss, and sequential tensioning loss in post-tensioning (He *et al*. 2022). Long-term losses include creep, prestress relaxation, temperature differential loss, and loss due to elastic deformation, all of which develop over time (Davies and Fragiacomo 2011; Riccadonna *et al*. 2020).

Scholars have described the changes in prestress over time in timber/bamboo beams. Quenneville and Vandalen (1994a,b) proposed rheological models and equations for prestress relaxation in timber beams under different environmental humidity conditions. Fragiacomo and associates (Fragiacomo and Davies 2011; Fragiacomo *et al*. 2011; Davies and Fragiacomo 2011) derived the prestress loss of *LVL* timber beams under long-term loading. Palermo *et al*. (2011) extended this model to other cable profiles such as catenary or parabolic and multi-span beams, providing a unified design procedure. Chen and Feng (2013) derived and validated the initial prestress formula for pre-tensioned *FRP*-strengthened timber beams with 3 *CFRP*-reinforced timber beams. Lv *et al*. (2019a,b) studied a novel *BFRP*-reinforced bamboo beam, categorizing prestress loss into 4 parts and proposing a method for effective prestress calculation. Based on experimental results, Fojtík *et al*. (2023) established an effective prestress expression for prestressed glued laminated timber beams. The prestress loss calculation methods summarized in each study are depicted in Table 1.

Table 1. Prestress Loss Calculation Model

Author	Formula
Quenneville and Vandalen 1994a, 1994b	$P=\left(P_0-wu_{\mathrm{r}}\right)\mathrm{e}^{-C_l t}\left(1-\frac{w}{NC_l}\right)+wu_{\mathrm{r}}+w\left(\frac{P_0-wu_{\mathrm{r}}}{NC_l}\right)$
	$C_1=\frac{w}{N}+\frac{k_s k_n}{N\left(k_s+k_n\right)}$
Davies and Fragiacomo, 2011; Fragiacomo and Davies 2011	$\sigma_p(t)=\sigma_{p,0}\left[1-r_p(t)\right]+\int_0^t E_p\left[1-r_p(t-\tau)\right]d\left(\varepsilon_p(\tau)-\varepsilon_{p,\mathrm{in}}(\tau)\right)$
Granello *et al.* 2020	$P_L(t)=P_0\left(1-0.0036t^{0.351}\right)$ $P_{UL}(t)=P_0\left(1-0.00076t^{0.523}\right)$
Chen and Feng 2013	$\sigma_0=E_f d_a \gamma_w f\left[\coth\frac{fl_e}{2}+\frac{f\left(l-l_e\right)}{2}\right]$
	$f=\sqrt{\frac{G_a}{dt}\left(\frac{1}{E_f}+\frac{\alpha}{E_w}\right)};\alpha=4\frac{d_f}{h}$
Fojtik *et al.* 2023)	$P=8.538-0.014day$
Note: The meaning of the letters is given in the appendix.	

Zheng *et al.* (2019) systematically proposed the calculation method for the prestress loss in prestressed *CFRP* plate-strengthened *GLT* beams. The prestress loss was divided into two parts. The first batch of prestress loss included cushion deformation and timber elastic deformation loss, while the second batch of losses included *CFRP* prestress relaxation, seasonal temperature difference, and timber creep loss. Based on the assumption of plane cross-section and the relationship between force balance and deformation coordination, the formula for prestress loss in *FRP*-reinforced glued laminated beams was established, as exhibited in Table. 2.

Researchers have also conducted controlled evaluation of prestress loss. Brunner and Schnüriger (2005) employed gradient anchorage technology, using an electronic control device to bond the prestressed laminate to the timber beam, addressing the issue of delamination. Dagher and Altimore (2005) developed a novel device for applying prestress in *GFRP* plates, with measured prestress loss in *GFRP* after 12 days being less than 2% of the original initial stress. Giongo *et al.* (2013) utilized self-tapping screws and found that prestress loss was reduced probably because the screws transmitted the load deeper into beams, reducing compressive stress at the end of beams. Guo *et al.* (2018, 2021, 2022) increased the number of prestressed steel strands used for external prestressing from 2 to 4 and found a significant reduction in prestress loss. However, when the number increased to 6, there was no change observed in prestress loss. Zuo *et al.* (2016) conducted a 45-day long-term loading test on 10 prestressed *GLT* beams. The study revealed that as the quantity of steel reinforcement increased, there was a corresponding increase in total prestress value and total stress loss, while mid-span long-term deflection declined.

Table 2. Zheng's (Zheng *et al.* 2019) Prestress Loss Calculation Model

Types of Prestress Loss		Formula
The first batch of prestress loss	Loss in cushion deformation	$\sigma_{11} = \dfrac{\sigma_f}{1 + A_g \times E_f / \left(A_f \times E_g\right)}$
	Loss of elastic deformation of timber	$\sigma_{12} = \left(\dfrac{P}{A_f} - \sigma_{11}\right) \times \left(1 - \dfrac{1}{1 + \mu + 12\mu\delta_f^{\,2} / h^2}\right)$
		$\mu = \dfrac{E_f}{E_w} \times \dfrac{b_f}{b_w} \times \dfrac{d_f}{h_w}$
The second batch of prestress loss	Loss of *CFRP* prestress relaxation	$\sigma_{13} = \varphi \times \dfrac{P}{A_f}$
		$\varphi = a + b\log(t),\ a, b$ are linear coefficients
	Loss of seasonal temperature difference	$\sigma_{14} = \Delta T \times \lvert \alpha_{\mathrm{f}} - \alpha_{\mathrm{w}} \rvert \times E_f$
	Timber creep	$\sigma_{15} = (0.3 + 0.9) \times \left(\sigma_{12} / E_f\right) \times E_f$
Note: The meaning of the letters is given in the appendix.		

In summary, pre-arching, as an early commonly used prestressing method, is characterized by its simple principle. Early pre-arching timber/bamboo beams relied on external loads and movable supports. Recently, researchers are continuing to explore pre-arching methods through moisture-dependent swelling nature or bending curvature characteristics of the timber without external equipment. Compared to the pre-arching timber/bamboo beams, additional prestressed components can significantly enhance the ultimate load-bearing capacity and crack resistance, with more precise control of prestress accuracy and less prestress loss under long-term loads, meeting the requirements of industrial producing requirements. Additional prestressed components include bars, sheets, and plates, primarily made of steel and *FRP*. Prestressed steel bars can significantly enhance the flexural capacity of timber /bamboo beams, while steel plates exhibit superior performance in reducing crack propagation. In addition to steel prestressed components, *FRP* sheets and bars are also widely used in the reinforcement of bending-resistant timber/bamboo structures due to their excellent strength-to-weight ratio and corrosion resistance. Additionally, the performance of adhesives significantly affects the timber/bamboo beams with prestressed sheets. The properties of the binder, bonding methods, and the contact mechanism between *FRP* bars and timber beams need further investigation. Furthermore, prestress loss is an unavoidable issue in prestressed structures. The components of prestress loss and the methods for calculating prestress in timber/bamboo beams have no unified standards yet, and measures to reduce prestress loss require further innovation and exploration.

PRESTRESSED TIMBER/BAMBOO COMPOSITE COLUMNS

Unlike bending members, prestress in compressed components such as columns often appears in the form of lateral constraints, where the prestress can restrict lateral expansion, reduce column buckling, and enhance the column's compressive load-bearing capacity.

Traditional timber columns have defects of relatively low load-bearing capacity, large cross-sectional area, susceptibility to erosion, and vulnerability to insect damage. Peripheral constraint materials including steel and *FRP*, *etc*. are commonly adopted for the reinforcement of timber columns (Krishnan 2020; Xu *et al*. 2023). The reinforcement measurement could delay the local buckling of steel tubes and reduce the outward expansion of the timber (Wang *et al*. 2024). However, simple wrapping reinforcement offers limited mechanical performance enhancements for timber columns, with disadvantages such as low combination efficiency. Therefore, prestress is introduced into composite columns, applying initial lateral stress to the core timber through external wrapping materials. The reinforcement method using prestress places the core timber in a triaxial compression state upon encountering external loads, effectively limiting lateral deformation of the timber and avoiding stress hysteresis in steel (Krishnan 2020).

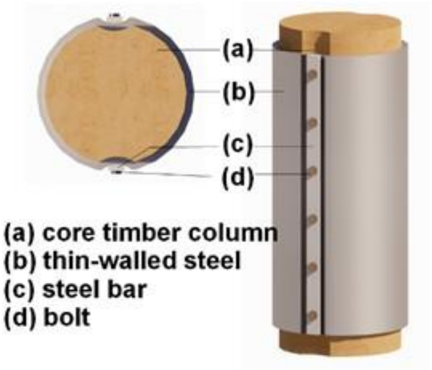


Fig. 7. Prestressed timber composite columns

Yang *et al*. (2018) utilized prestressed steel strips with different layers and spacing to reinforce cracked timber columns. The results demonstrated that the ductility and energy dissipation performance capacity of the cracked timber columns were enhanced, but steel strips had no significant impact on the stiffness. Li *et al*. (2019) and Wang *et al*. (2022) proposed a novel prestressed thin-walled steel tube confined timber column, where constraints were applied by a thin-walled steel tube. Bolt holes were punched into the steel strip, and the tightening force of bolts was the main measure to apply circumferential prestress, as shown in Fig. 7. Additionally, Li *et al*. (2019) also proposed a calculation model for the ultimate strength of the new prestressed steel-timber composite column, as indicated in Eq. 1,

$$\frac{F_{wc}}{F_{w0}} = 1 + 4.1\left(\frac{F_{il} + F_{el}}{F_{w0}}\right)^{0.8236} \tag{1}$$

where F_{wc} represents the ultimate strength of composite columns confined by prestressed steel tube, F_{w0} represents the ultimate strength of unconfined timber columns; F_{il} represents the initial lateral confining stress induced in the core timber column by the initial steel strain, and F_{el} represents the effective lateral confining stress induced in the core timber column by steel tube.

Qiu *et al*. (2021) developed a numerical model for prestressed thin-walled steel confined square timber columns. The numerical analysis results indicated that excessive prestress in composite columns could lead to yielding in parts of the steel, thus weakening the effect of active confinement and resulting in a lower ultimate load capacity. Wang *et al*. 2022) wrapped a *CFRP* sheet around the exterior of prestressed steel-timber columns. It was discovered that the addition of *CFRP* sheets significantly improved the ductility and axial load-bearing capacity of columns.

LATERAL RESISTING STRUCTURAL SYSTEMS

In terms of lateral resistance structures, prestress is also applied to the seismic performance enhancement of timber/bamboo structures (Nguyen *et al*. 2018; Smith *et al*. 2016). American and Japanese scholars have proposed resilient cities as the main direction for future research. Self-centering earthquake-resistant structures, as a type of resilient structures, have become one of the research hotspots in recent years (Froozanfar *et al*. 2024). The self-centering seismic system is a novel structural system that combines prestress and energy-dissipating technologies to realize seismic resilience (Amer 2023). Moreover, the self-centering design concept is also extended to the timber/bamboo structural systems, including self-centering timber/bamboo frame structures (Di Cesare *et al*. 2018; Iqbal and Popovski 2017; Shu *et al*. 2019) and self-centering timber/bamboo shear walls, *etc.* (Chen *et al*. 2024; Fitzgerald *et al*. 2020; Sun, *et al.* 2020). The specific implementation methods are described as follows.

Self-centering Frame Structures

The ductile design of traditional frame structures with strong columns and weak beams utilizes the plastic deformation of structural components to dissipate seismic energy (Nie *et al*. 2020; Park 1986). This kind of design results in a severe post-earthquake loss (Paulay 1986; Wongpakdee and Leelataviwat 2017). Consequently, prestress has been employed to connect beam-column joints in frame structures, effectively addressing this issue. Palermo *et al*. (2005), based on Priestley’s theory (Priestley and Calvi 1991), which pioneered the low-damage design of reinforced concrete structures, proposed a multi-*LVL* seismic-resistant frame system using post-tensioned tendons connections called Prestressed-Laminated (*Pres-lam*) systems. This method adopted unbonded prestressed tendons to connect the structural components. Internal energy steel bars were adopted to dissipate energy, thus resulting in a special ‘flag-shaped’ self-centering dissipative hysteresis loop as shown in Fig. 8.

Newcombe *et al*. (2008) proposed a novel seismic resisting system for multi-story timber buildings, integrating improved ductile steel connections based on the post-tensioning method and rocking timber frames. The connections between beams and columns involved *LVL*, unbonded post-tensioned tendons, and energy dissipaters. Iqbal *et al*. (2016) conducted full-scale tests on Newcombe’s system, using both steel dissipaters and unbonded post-tensioning mild steel reinforcement. This hybrid system offered significantly higher energy dissipation compared with schemes relying solely on steel bars. Iqbal *et al*. (2018) also studied the mechanical behavior of post-tensioning connections with specific energy dampers, achieving near-zero residual deformation. Sarti *et al*. (2016)

proposed a *CW*C (column-wall-column) rocking column-shear wall hybrid system, where vertical prestressed steel bars were tensioned within the timber walls, and U-shaped steel plates served as additional overturning moment resistance and energy dissipaters. Wei and associates (Wei *et al*. 2024; Wu *et al*. 2014) conducted experiments on rigid timber wall panels equipped with slip-friction connectors, which imparted ductility and elastoplastic characteristics to brittle structures.

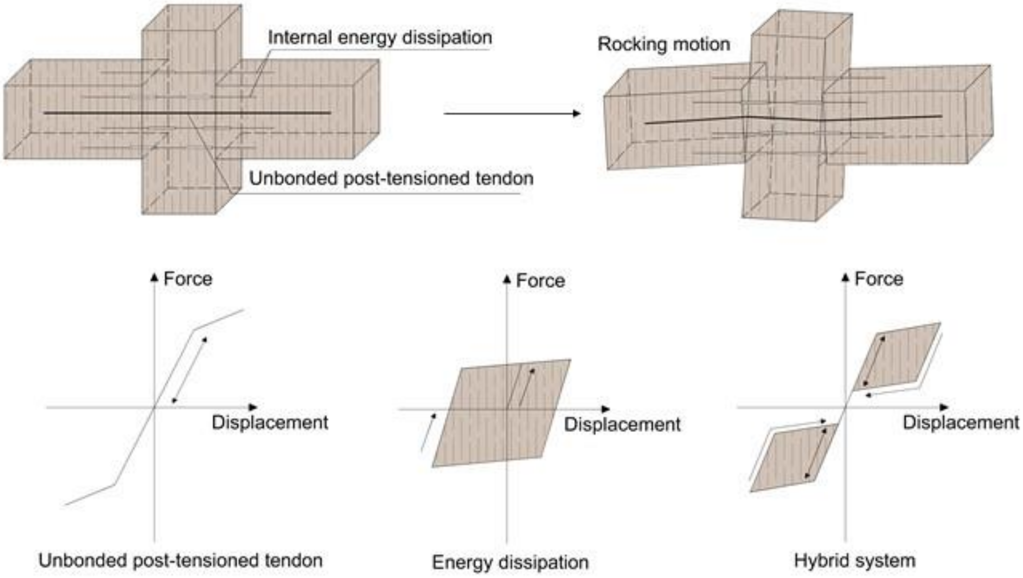


Fig. 8. Palermo's model (Palermo *et al.* 2005; CC0 1.0 Universal)

Di Cersare *et al*. (2017, 2018, 2020) conducted dynamic tests on a three-story post-tensioned timber frame structure equipped with an energy-dissipating brace system. The elastic seismic performance was enhanced by coupling the post-tensioned frame with the energy-dissipating braces. Smith *et al*. (2014, 2016) conducted experimental research on inclined steel plate post-tensioned *GLT* connections and observed strong self-centering and energy dissipation capability. Wanninger and Frangi (2014), Wanninger *et al*. (2015) and Granello *et al*. (2018, 2019) conducted a series of pushover tests on post-tensioned timber structural frames. The results showed that these connections presented low damage levels in tests. Li *et al*. (2020) compared the performance of hybrid post-tensioned *GLT* connections with tenon connections and concluded that post-tensioned timber connections exhibited smaller residual deformations.

Self-centering Shear Walls

Although traditional shear walls using nailed or bolted connections have been shown to have high strength and stiffness, their deformation capacity is limited in earthquakes (Aloisio *et al*. 2023a; Brown *et al*. 2022). The shear walls exhibited brittle characteristics in an earthquake, leading to stiffness degradation, substantial base shearing, severe connection damage, *etc*. (Li *et al*. 2018; Hasani and Ryan 2022). Consequently, scholars have investigated self-centering rocking or shear wall systems using post-tensioned prestressed connections (Miliziano *et al*. 2020; Piri and Massumi 2022; Brown *et al*. 2023). This structure employed vertical prestressing tendons to pre-compress the walls to the foundation, supplemented with small energy-dissipating components such as

U-shaped flexural plates (UFP) or post-tensioned (PT) tendons (Sun *et al*. 2020; Wilson *et al*. 2020), as shown in Fig. 9. Under seismic actions, gap openings were present at the bottom of the walls, thus effectively controlling structural damage and reducing residual displacements (Aloisio *et al*. 2023c; Brown *et al*. 2023). In addition, the energy-dissipating components enhanced the energy dissipation capacity of the structure, further mitigating the seismic response (Cui *et al*. 2020; Piri and Massumi 2022).

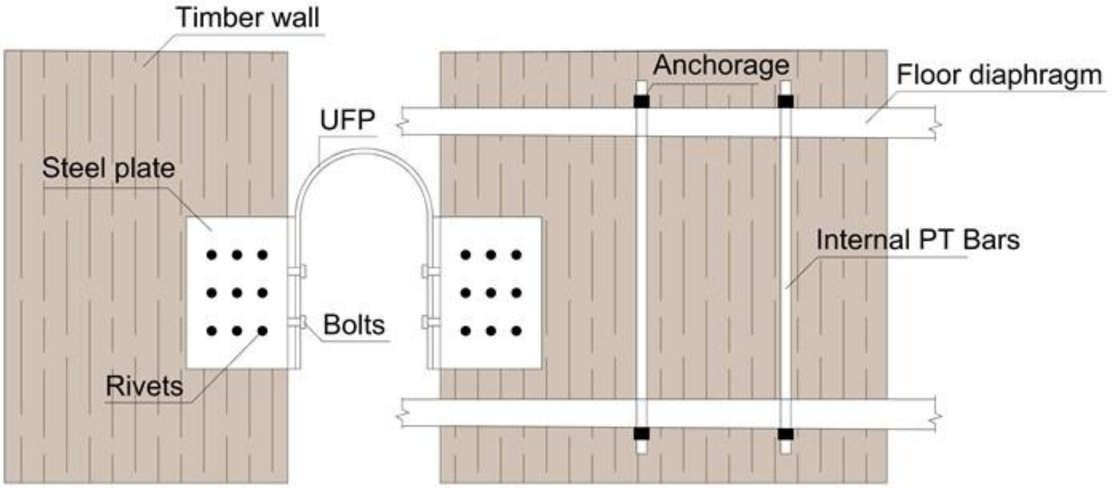


Fig. 9. UFP and PT

Iqbal *et al*. (2015) proposed a new form of self-centering rocking wall coupled with PT tendons and UFPs as energy dissipation devices. UFP dissipaters exhibited stable energy dissipation characteristics and an ideal flag-shaped hysteresis behavior was achieved by combining UFPs with PT tendons. Ganey *et al*. (2017) described experiments conducted to develop a resilient wall system that combined cross-laminated timber (*CLT*) panels with vertical PT tendons to provide post-earthquake recovery.

He and associates (Chen *et al*. 2021; He *et al*. 2022; Li *et al*. 2023) introduced a new type of self-centering steel-timber hybrid shear wall system (SC-STHSW), which employed post-tensioned tendons for the connection of frame beam-column joints, with slip friction dampers serving as connectors between the frame and the wall. Low-cycle quasi-static tests on this system revealed that the SC-STHSW system exhibited unique flag-shaped hysteresis characteristics. The prestressed connection method effectively controlled residual deformations of the structure, and the additional friction dampers enhanced the energy dissipation capacity. Lu *et al*. (2022, 2024) proposed a self-centering *CLB* (cross-laminated bamboo) rocking wall structural system using two kinds of friction dampers: traditional friction dampers and novel bending-friction coupled dampers (BFCD). The results obtained from quasi-static tests and finite element analyses indicated that the BFCD provided higher stiffness and energy dissipation capacity under a high drift ratio.

Traditional frame structures and shear wall structures are two different structural forms. A lateral force-resisting system composed of beams and columns is used in frame structures to withstand seismic actions, while shear wall structures resist seismic actions through their own bending and shear stiffness. Compared to frame structures, shear wall systems are more suitable for high-rise buildings, with a maximum applicable height of up to 140 meters in seismic design.

Based on traditional frame systems, self-centering timber frame structures originated from Palermo's (2005) research on the low-damage prestressed laminated (*Pres-*

Lam) system. Unbonded post-tensioned tendons connect the timber structural members, forming connections that resist seismic forces and dissipate energy, thereby overcoming the stiffness degradation and connection damage issues faced by traditional frames during earthquakes. Unlike the self-centering timber frame mechanism that uses press at beam-column joints, the self-centering timber shear wall system uses vertical prestressing tendons to press the wall to the foundation, supplemented by small energy-dissipating components such as *UFP*s. This approach reduces residual displacement and enhances energy dissipation capacity.

PRESTRESSED LARGE-SPAN TIMBER STRUCTURAL SYSTEMS

In large-span structures, buckling is a crucial factor affecting the strength and stability of the structure as spacing increases (Fraternali and Motta 2023). Consequently, components of large-span structures should be designed to be axially loaded to ensure performance stability (Crocetti 2016; Dietsch and Winter 2018). Moreover, due to the large number of components in large-span structures, there are high demands on connection performance. Therefore, existing studies have applied prestress to large-span structures through the string approach. This structural system originated from the concept of tensioning the beam *via* chords through rods (Saitoh 1998; Saitoh and Okada 1999). The short rods were placed under the beam, applying prestress to the beam via cables, as shown in Fig. 10. The compressive force on the rods created a counter moment and reverse deflection in the upper chord structure, thus reducing the maximum moment and final deflection under external loads, and improving the structural stress distribution (Nie and Li 2012). The string method was also applied in the timber/bamboo large-span structures.

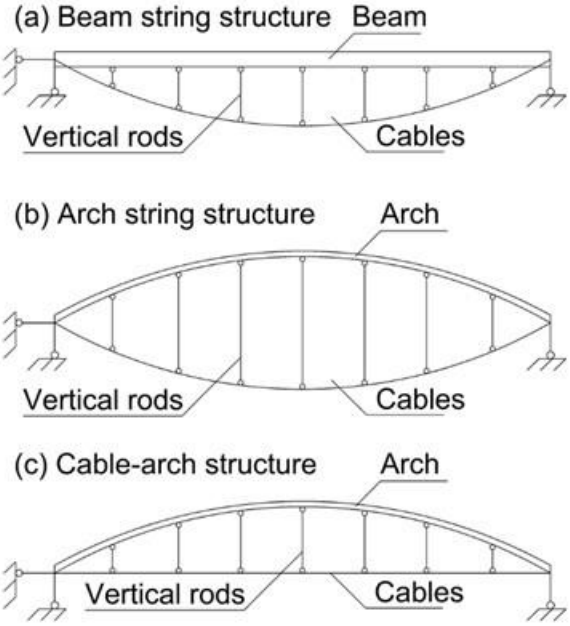


Fig. 10. Types of string structures

Plane String Structures

The concept of plane string structure was first used in the 138.7-meter-long Royal Albert Double-Span Railway Bridge in 1859 (Norrie 1956), as shown in Fig. 11. Masao Saito defined the beam chord structure at the IASS Symposium as a self-balancing system composed of compressive and tensile components connected by vertical rods. Plane string timber/bamboo structures have also been investigated (Zhao *et al*. 2024). Current research has employed analytical methods, finite element analysis, and model testing to study the performance of plane timber/bamboo string structures, including the number of vertical rods, initial geometric defects, and material elastoplastic (Lee *et al*. 2023).

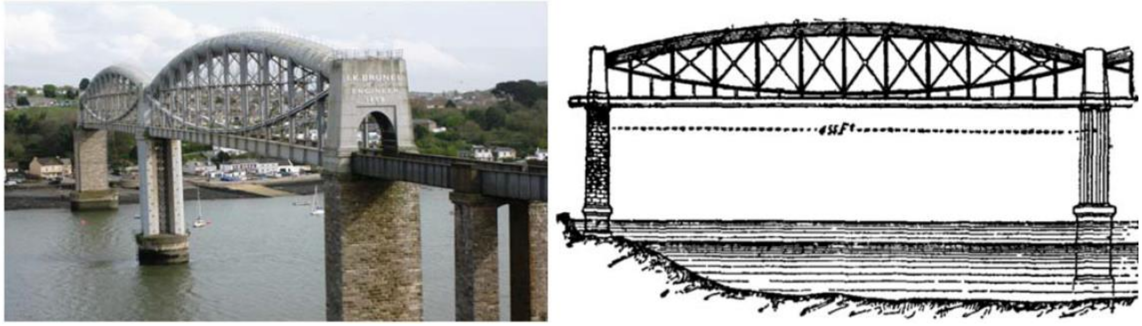


Fig. 11. Royal Albert Double-span Railway Bridge (*https://en.wikipedia.org/wiki/Royal_Albert_Bridge#cite_note-3*)

Zhang *et al*. (2014) conducted compressive tests on the glued string beams and concluded that increasing the arch-span ratio or sag-span ratio could enhance the load-bearing capacity. Guo *et al*. (2019) employed experimental and numerical research to explore factors affecting the performance of string truss *GLT* beams, finding that the stronger the compressive performance increased with the number of prestressing steel wires and the magnitude of the prestress. String truss *GLT* beams exhibited a ductile failure mode. Bending tests were conducted by Sun *et al*. (2016) on plane string beams with additional prestressed steel strands on the lower chord. The results showed that the brittle failure mode in ordinary beams was transformed into a plastic failure mode, with their ultimate load-bearing capacity and stiffness inversely proportional to the span ratio. Zhao *et al*. (2023) conducted five-point bending tests on large-span glulam string beams. The results indicated that as the diameter increased, the failure region shifted from the lower steel cable to the upper composite beam.

Fig. 12. Horinouchi Town Gymnasium in Japan (https://data.shinkenchiku.online/en/projects/articles/SK_1996_12_240-0)

Plane string structures are suitable for complex architectural forms, with broad application prospects. The Horiuchi Town Gymnasium in Japan (Saitoh 1998), with a 38 m span, exemplified a timber plane string structure using composite truss beams, as exhibited in Fig. 12. Situated in a snowy region of Japan, the design considered a snow depth of up to 3.5 m. Ingeniously, diagonal rods and columns were added to the string beams; thus, the rigidity of the string components was increased during heavy snow-loading conditions.

Spatial String Structures

Spatial string structures are formed from plane string configurations arranged in specific spatial layouts. Common types include bidirectional, multidirectional, and radial spatial string structures (Yifeng and Jian 2011). Due to the complex forces involved, modeling experiments on spatial string structures are challenging. Consequently, scholars often utilize numerical analysis methods for research (Cantcheff 2011).

Rumlová and Fojtík (2015) used finite element analysis to study the strain changes at critical joints in spatial timber roof supports. Sejkot *et al*. (2020) examined the lateral stability of single and bidirectional timber string roof structures through numerical simulation and geometric nonlinear analysis. The results revealed that lateral torsional buckling of the top chords adversely affected the load-bearing capacity against out-of-plane buckling. Ching and Carstensen (2022) developed a topology optimization algorithm for steel-timber hybrid spatial string structures, aimed at reducing carbon emissions.

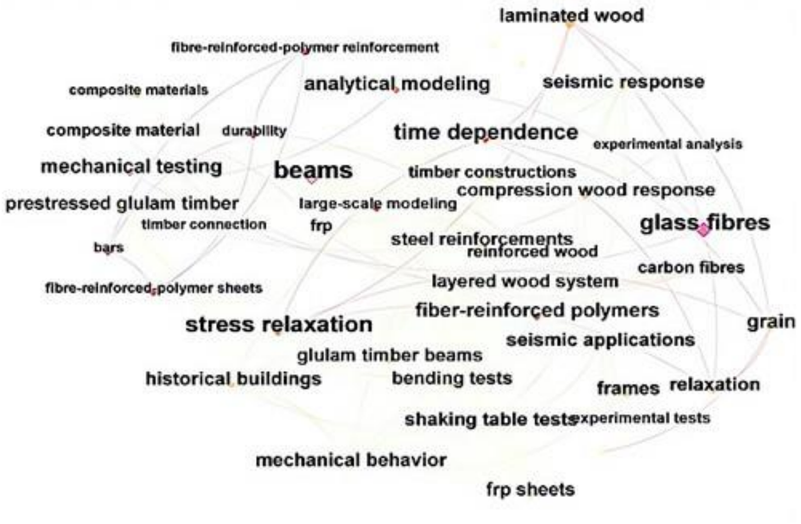
The Izumo Dome in Japan, completed in 1992, was a typical application of timber spatial string structures, featuring a spatial arch string structure with a diameter of 140 m and height of 49 m (Tsubota *et al*. 1993). Composed of radial wooden arches and a lower cable system, the structure was covered with an external membrane, as illustrated in Fig. 13. The dome was entirely assembled on the ground, elevated and heightened through a central temporary support structure, lifting the dome into place.

Fig. 13. The Izumo Dome in Japan (*https://en.wikipedia.org/wiki/Izumo_Dome*)

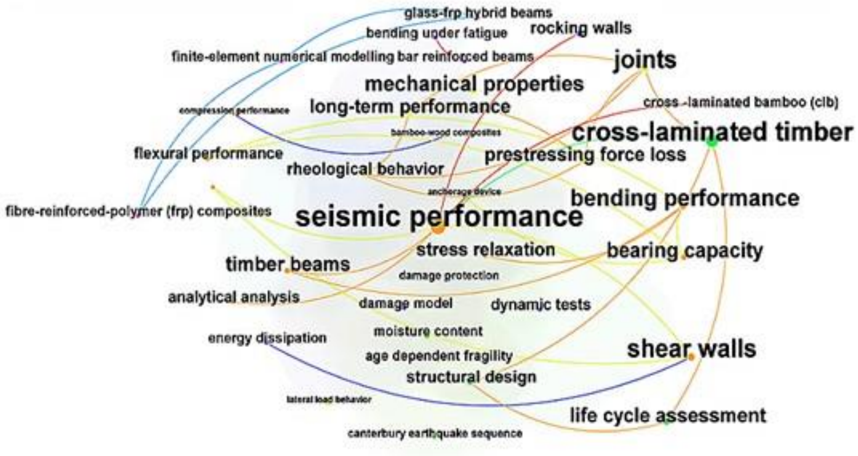
Plane string structures primarily extend within a two-dimensional plane and are commonly found in roofs and bridges, including forms such as beam string structures, arch string structures, and cable-arch string structures. Spatial string structures are composed of plane string structures arranged in specific spatial configurations, including bidirectional string structures, multidirectional string structures, and radial string structures, which are more suitable for large-span structural roofs. Research on modern timber/bamboo string structures is still relatively limited, requiring further study on their load-bearing mechanisms and seismic performance to promote their engineering applications.

BIBLIOMETRIC ANALYSIS ON PRESTRESSED TIMBER/BAMBOO STRUCTURES

Recent research hotspots were identified in this work through statistical analysis. Knowledge maps depicted innovative developments and forecasted future directions (Börner *et al*. 2003). The primary research corpus was sourced from the Web of Science database, with data mining facilitated by CiteSpace. Keyword trend analysis, as shown in Fig. 15, elucidated development hotspots, revealing a shift in research focus towards structural seismic resilience over the past two decades. Efforts have concentrated on understanding the mechanical behavior and performance characteristics of individual components, laying theoretical foundations for practical engineering applications.



(a) 2000-2015



(b) 2015--2024

Fig. 14. Keywords analysis

However, translating research findings into practical engineering applications remains limited with unresolved issues:

(1) Efficient timber/bamboo component reinforcement schemes

Currently, combining steel and *FRP* can mitigate the shortcomings of timber/bamboo materials. Steel is prone to corrosion and is heavy, while timber/bamboo materials are hygroscopic. Timber/bamboo beams reinforced by *FRP* may face problems including reduced bonding or delamination, aging, humidity, temperature fluctuations, *etc*. Consequently, the development and research in novel strong, lightweight, durable, and economical materials for reinforcing timber/bamboo components and structures are needed.

(2) Evaluation and control of prestress loss

Timber/bamboo structures are sensitive to environmental humidity and temperature changes. Creep can easily cause prestress loss, affecting long-term performance and threatening durability. Research on prestress loss could help predict and control the effectiveness of prestress more accurately in practical design. Currently, there is no unified standard for calculating prestress loss in prestressed timber/bamboo components and connections. Therefore, further research is needed on the long-term performance considering prestress loss.

(3) Novel prestressed timber/bamboo structural systems

Currently, there is no widely applied form of prestressed timber/bamboo structures. Prefabrication of timber/bamboo structures is a key focus of future research in structural engineering. By reasonably combining prestressed components or additional parts, modular units can be achieved, promoting prefabricated design and production. There is an urgent need for novel structures that can be rapidly assembled and possess stable seismic performance. This will effectively ensure construction safety in earthquake areas and reduce the damage caused by seismic disasters.

CONCLUDING REMARKS

Since the 1950s, extensive research has been conducted by scholars on prestressed timber/bamboo structures, initially focusing on the mechanical performance of individual components post-tensioning, gradually shifting to the overall structural performance. This paper has provided an overview of the historical development and latest advancements in prestressed timber/bamboo structures from the component, connection, and structural levels, as shown in Fig. 15. This study utilized bibliometric analysis to summarize existing research, identifying the issues remaining to be addressed and future development directions in the field of prestressed timber/bamboo structures. The main research conclusions are as follows:

(1) To address the shortcomings of low stiffness and susceptibility to deformation in timber/bamboo flexure components, external load pre-cambering and additional prestressed components are used to reinforce timber/bamboo flexural components. The results indicate that when retrofitted with prestress, timber/bamboo flexural components present improved ultimate bearing capacity, ductility, and stiffness. Meanwhile, prestress loss in prestressed reinforced bending components is inevitable. Further research on the

long-term performance of prestressed timber/bamboo structures considering prestress loss is necessary.

(2) Prestress in timber/bamboo columns often appears in the form of lateral confinement. Thin-walled steel tubes are commonly used to constrain the timber columns. Circumferential prestress is applied to the thin-walled steel through bolt-tightening force, placing the core timber column in a triaxial compression state when subjected to external loads. Prestressed steel-timber composite columns can enhance the ultimate compressive bearing capacity of the columns, improving ductility and energy dissipation characteristics.

(3) Self-centering lateral resistance timber/bamboo structures can enhance seismic performance through prestress technology. Self-centering timber/bamboo frames and shear wall systems have continuously developed over the past two decades. The combination of prestressed connections and additional energy-dissipating components can effectively control seismic damage, achieving excellent flag-shaped hysteretic performance. However, such structures have not yet been widely applied. The actual seismic response and anti-collapse performance need further investigation.

(4) Existing research applies prestress to timber/bamboo large-span structural systems through the string method, changing their failure mode to ductile failure. Timber/bamboo string structures are favored for their elegant and smooth configuration and spatial sense, with practical applications such as the Izumo Dome in Japan. To promote the development of such structures, further research is needed from the perspectives of numerical simulation, theoretical study, and model testing, especially considering the long-term performance of structures with varying prestress.

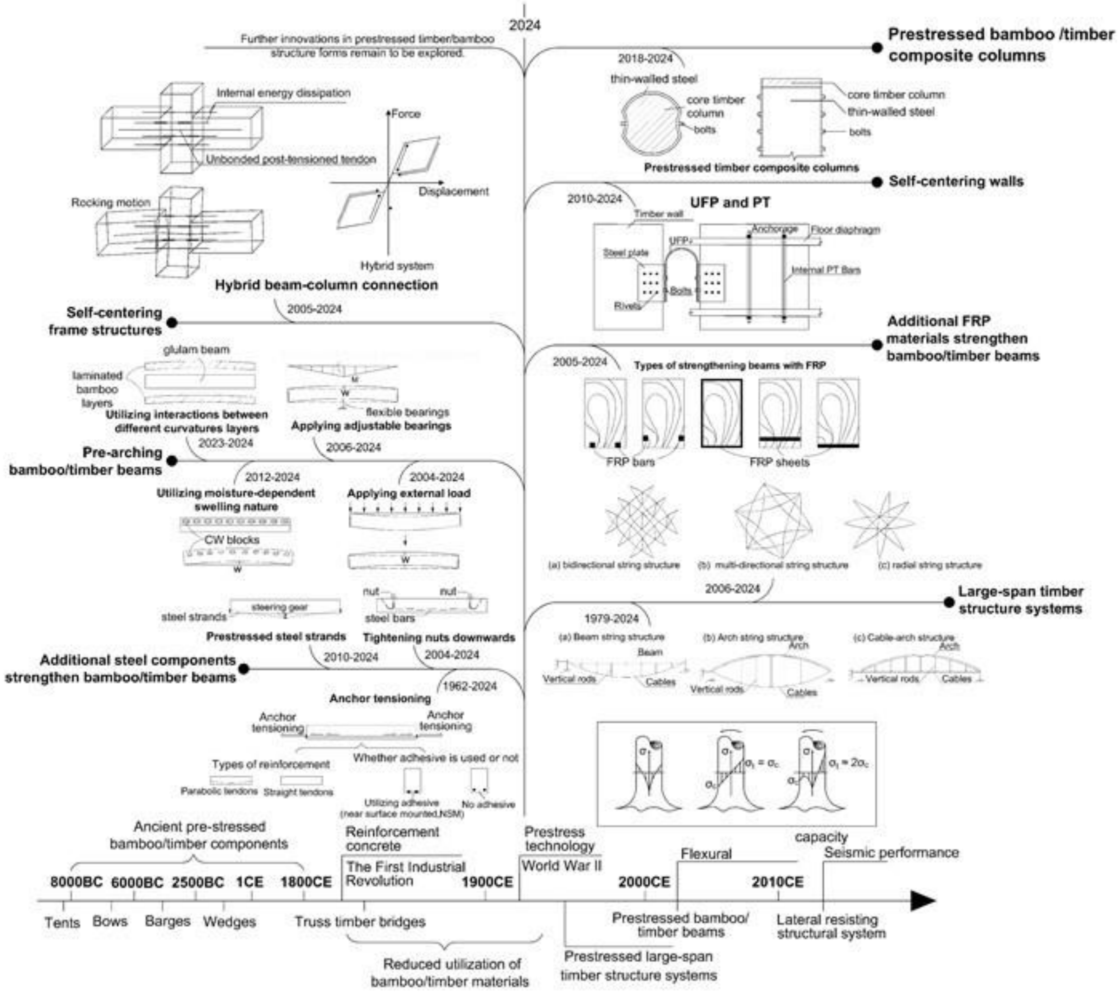


Fig. 15. Overview of the history and recent advances in timber/bamboo structures

Despite significant progress in various prestressed timber/bamboo structures, practical engineering applications remain limited. In addition to technical considerations, the economic implementation of prestressing technology requires comprehensive life-cycle cost assessments. Additionally, it is necessary to translate research achievements and existing engineering experience into design codes and standards. Advances in materials science, structural testing, and computational technology will further promote the development of prestressed timber/bamboo systems, contributing to greener and more sustainable urban construction.

ACKNOWLEDGEMENTS

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LIST OF SYMBOLS

Symbols	
P	prestressing force
w	weight constant
u	fluid displacement
t,τ	time from prestressing
N	amping constant
k	spring stiffness
σ	stress
r	relaxation coefficient
E	young's modulus
ε	total strain
ε_{in}	environmental (thermal and moisture) strain
d	thickness
γ	shear strain
l	length
G	shear modulus
h	height
day	number of the day from the beginning of prestress
A	section area
δ	initial eccentricity
ΔT	temperature range between environment and anchored rebars
α	coefficient of temperature expansion
F	ultimate strength

Subscripts	
0	refers to initial value at t=0
r	refers to reservoir in dashpot reservoir element of relaxation model
s	refers to stressing system in relaxation model
n	refers to wood element in relaxation model
p	refers to prestressing steel
L	refers to loaded beam
UL	refers to unloaded beam
f	refers to *FRP*
a	refers to the adhesive layer
w	refers to wood
e	refers to elastic area
g	refers to cushion blocks under beams

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