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Advancing Timber for the Future Built Environment

AN EXPERIMENTAL INVESTIGATION ON THE LONG-TERM BEHAVIOR OF PRESTRESSED GLULAM BEAMS

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ABSTRACT: The flexural behavior of glued laminated timber (glulam) beams could be efficiently improved by the prestressing technology. However, there is still limited research on the long-term behavior of prestressed glulam beams. To address this challenge, this paper presents an experimental investigation on the long-term flexural behavior of internally prestressed glulam beams. Two groups of glulam beams under same prestressing force, unloaded or loaded by four-point bending, were continuously monitored for over 450 days in an indoor space without environmental control. The influences of environmental factors including relative humidity, temperature and loading patterns on the moisture content, prestressing force, deflection and strain were examined. It was observed that environmental factors, particularly relative humidity, significantly affect the long-term behavior. The difference of changing trend between relative humidity and the direction of strain significantly influence long-term strain behavior. Unloaded samples exhibited a higher prestress loss, 10.2%, compared to 6.7% of loaded samples. The entire changing trend of long-term deflection was primarily influenced by the loading pattern and dominated by wood creep. Unloaded samples exhibited a higher relative change of deflection, 52.8%, compared to 27.3% of loaded samples.

KEYWORDS: timber structures, bending, creep, posttension, steel strand.

1 – INTRODUCTION

Advancing prestressing technology of engineered wood products is essential for the development of mass timber structures. The growing demand for sustainable construction materials has attracted interest in enhancing timber structures, particularly prestressing timber (PT) systems, which integrate the ecological benefits of timber with enhanced structural performance. Since the introduction of PT technology in 2005 by Palermo et al. [1], there have been increasing studies on PT members [2][3]. Furthermore, PT has been implemented in a variety of building projects [4][5].

Timber beams, when eccentrically prestressed, exhibit enhanced serviceability through reduced deflection and increased load-bearing capacity, making them cost-effective for long-span applications. In 2010, Palermo et al. [6] applied this technology to long-span post-tensioned laminated veneer lumber (LVL) beams and developed a nonlinear iterative procedure that accounts for tendon elongation to predict the serviceability behavior. Smith et al. [7] extended this method to post-tensioned timber frames. In 2016, Yang et al. [8] fabricated glued laminated timber (glulam) beams pretensioned with carbon fiber-reinforced polymer (CFRP) bars, achieving significant improvements in serviceability. Further advancements were made by employing bonding methods in post-tensioned beams, where the use of adhesives effectively distributes the increased stress from the tendon to the timber, preventing excessive pressure at the beam ends. The substantial improvement in the flexural behavior has been validated and investigated by McConnell et al. [9], Zhang et al. [10], and Wang et al [11].

Nevertheless, the long-term reliability of such systems remains a critical concern due to wood's inherent hygroscopicity and creep behavior. These properties make timber susceptible to environmental fluctuations and stress redistribution, complicating predictions of structural performance over decades of service. Recently, with the rapid advancement of prestressing timber technology, an increasing number of studies have focused on the long-term behavior of posttensioned timber structures. In 2011, Davies and Fragiacomo

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[12][13] conducted a long-term monitoring on posttensioned LVL beams and frames over 1 year under both uncontrolled and controlled environments. They identified key parameters including environment conditions and the ratio of beam length to column depth. Subsequently, a formula was proposed to describe the long-term prestress loss based on the age-adjusted effective modulus method. In 2015, Wanninger et al. [14] investigated the long-term behavior of posttensioned glulam joints and predict the prestressing loss during service life by the previous model [13] for beam-column joint details. In 2017, Grellano et al. [15] performed a four-year bending test on unbonded post-tensioned LVL beams, revealing that unloaded and loaded prestressed beams experienced prestress losses of 3.4% and 4.5%, respectively, which are predicted to reach 11%-13% over a 50-year period. In 2020, Granello et al. [16] reported two-year monitoring results from an operational post-tensioned mass timber building, the House of Natural Resources. A numerical model that considers moisture-dependent viscoelasticity showed satisfactory agreement with the experimental prestressing force data. Zheng et al. [17] conducted a 750-day monitoring study on post-tensioned glulam joints with varying prestress ratios and structural details. The numerical analysis indicated that unreinforced joints experienced a prestress loss exceeding 50%, while those reinforced with steel exhibited significantly less loss.

Given the significant creep characteristics of wood and the enhancing effect of prestressing force, there's an urgent need for comprehensive experimental data on the long-term performance of prestressed glulam beams. A complex mechanical relationship is presented, as the prestressing force, serving as an internal self-balancing force, is inherently coupled with the deformation state of the structural member. This interdependence, combined with external loading conditions, creates a sophisticated mechanical system. To address these research gaps, this study conducts an experimental investigation on the long-term behavior of prestressed glulam beams. The experimental project involved four beams subjected to different loading patterns, unloaded and loaded, over an extended period. Through this investigation, the key factors influencing long-term performance indicators, including moisture content change, prestressing force evolution, deflection development, and strain were analyzed.

2 – EXPERIMENTAL PROJECT

2.1 TEST SAMPLES

Two groups of prestressed glulam beams, each 2 replicates, were fabricated and tested. These two groups have the same configuration and prestressing force but different loading patterns: only prestressed or both prestressed and loaded. Additionally, an environmental sample with 1000 mm long and having the same cross section was used to investigate the environmental effects. The details are listed in **Table 1** and shown in **Fig. 1**. To avoid creep failure, the load applied to Group B2 was set significantly below the peak value reported in a prior test **[11]**. All test samples were fabricated by glulam beams with a dimension of 120 mm × 200 mm × 2600 mm and a slot in the lower half of the cross-section. Douglas fir laminas were used to construct glulam beams and there was no surface coating.

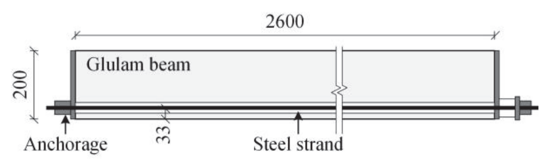

Figure 1. Configuration of test samples——B1 and B2.

Table 1: Overview of test samples.

Group	Prestressing force	Load
B1	55 kN	0 kN
B2	55 kN	15.9 kN
EN	~	~

2.2 TEST SETUP AND EXPERIMENTAL PROCEDURE

All beam samples were arranged in a simply supported configuration with a span length of 2400 mm. Group B1 was exclusively placed in the supports. Additionally, Group B2 was continuously loaded using a device that allowed for the timely maintenance and adjustment of the vertical force, as shown in **Fig. 2**. Group EN was simply positioned without any additional constraints.

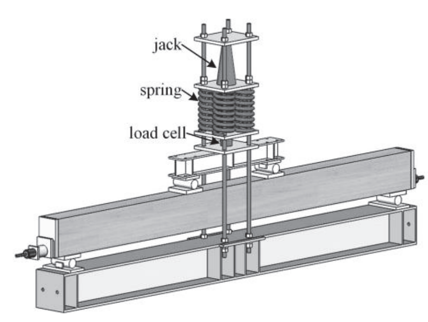

Figure 2. Test setup of loaded group B2. Group B1 was placed in the support with a same span as B2.

The layout of sensors was shown in **Fig. 3**. The long-term change of relative humidity, temperature, moisture content, prestressing force, deflection and strain were

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monitored. The moisture electrodes were installed at a depth of approximately 40 mm in the middle layer. The strain points were monitored by mechanical strain gauge and installed at the edge of the mid-span cross section.

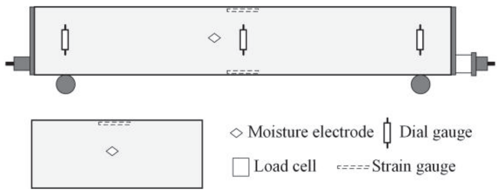

Figure 3. Layout of monitoring points.

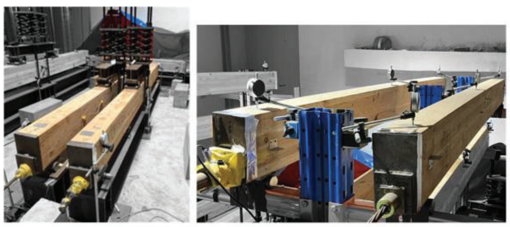

Figure 4. Picture of the test samples.

The test was conducted in a laboratory in Shanghai without humidity or temperature control. The experimental procedure comprised the following steps:
(1) assembling test samples and arranging all sensors;
(2) tensioning the steel strand to apply prestressing force;
(3) installing the loaded samples in the device and loading in 1 month after posttensioning.
Thereafter, the samples were continuously monitored for over 450 days. Data collection was initially conducted daily for the first 3 months, after which the frequency gradually decreased. The test samples in place were shown in **Fig. 4**.

4 – EXPERIMENTAL RESULTS

4.1 ENVIRONMENT AND MOISTURE CONTENT

The environmental relative humidity and temperature during the test period are illustrated in **Fig. 5**. The temperature exhibited remarkable changing trend in a year, where the temperature reached maximum in summer and minimum in winter. In contrast, the relative humidity did not exhibit significant seasonal change. Given that the laboratory is exposed to outdoor conditions, rainfall emerges as the predominant factor influencing humidity.

The long-term moisture content of wood is illustrated in **Fig. 6**. It can be observed that the trends and amplitudes of moisture content across different samples were similar, primarily attributed to their comparable initial moisture levels. The environmental sample exhibited slightly higher values due to its shorter length, indicating that moisture diffusion perpendicular to the grain is the dominant factor. The relationship between moisture content and relative humidity demonstrated a substantial influence of environmental humidity on the moisture change in beams with untreated surfaces. In the short term, changes in moisture content closely paralleled those in relative humidity. Over the long term, the moisture content showed an increasing trend during the first seven months, as the equilibrium moisture content (EMC) exceeded the initial moisture content.

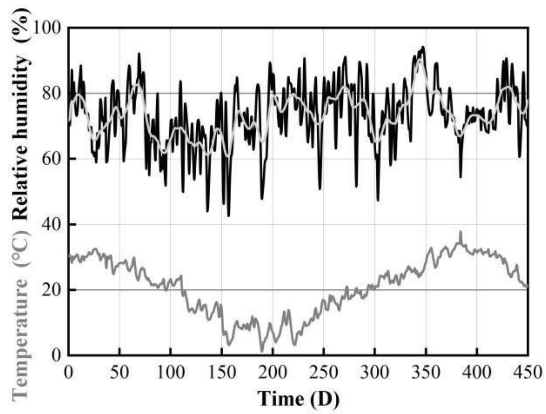

Figure 5. Relative humidity and temperature.

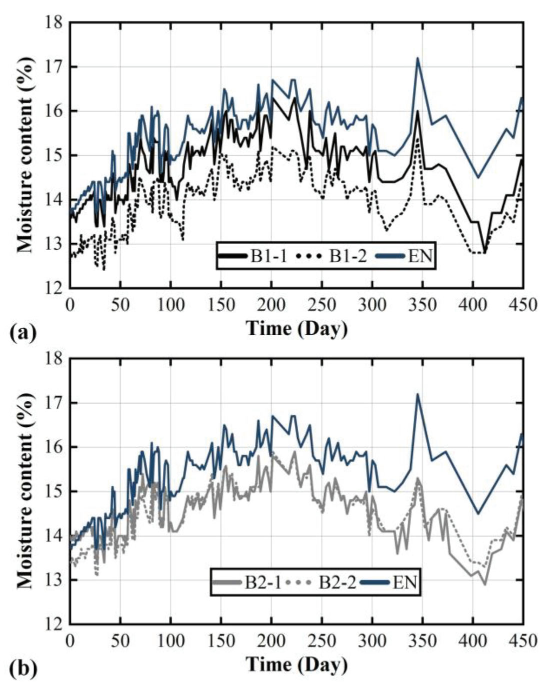

Figure 6. Moisture content: (a) unloaded Group B1 and (b) loaded Group B2.

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4.2 STRAIN

The strain changes are illustrated in Fig. 11. Due to the prestressing force, the tensile strain of bottom fiber in Group B2 was maintained at a lower level. It can be observed that environmental strain exhibits a similar change trend due to variations in relative humidity, as the testing points are located on the surface. Thus, environmental strain tends to increase positively with rising relative humidity. Within the same group, despite the absolute value of initial tensile strain being significantly lower than that of initial compressive strain, tensile strain demonstrates even higher short-term fluctuations and similar long-term changes compared to compressive strain. Overall, environmental factors and the direction of strain significantly influence long-term strain behavior.

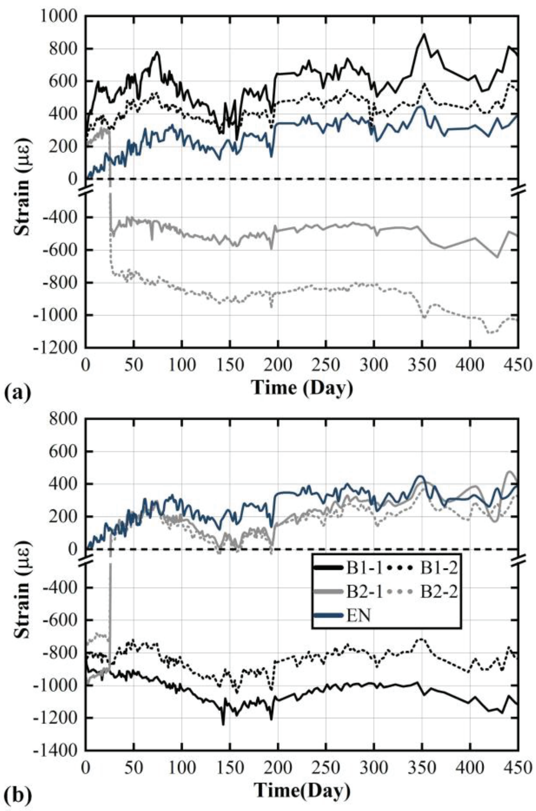

Figure 7. Strain: (a) top fiber; (b) bottom fiber.

4.3 PRESTRESSING FORCE

The experimental results of the prestressing force and its relative change are illustrated in **Fig. 7** and **Fig. 8**. The relative change of loaded group B2, defined as the ratio of the long-term change to the elastic change caused by applying the prestressing force or vertical load.

For the short-term changing trend in prestressing force, it was closely followed that of moisture content, primarily due to the swelling and shrinking behavior of wood parallel to grain. Meanwhile, the temperature change caused a seasonal thermal change of prestressing force, including the increase within the 150th-250th day and the decrease within the 350th-400th day. In the first month, the prestressing force exhibited a rapid decrease as a result of the initial rapid propagation of creep deformation in wood. Subsequently, as the influence of wood creep diminished, moisture-induced deformation became more dominant. Consequently, the entire decreasing trend was not remarkable until one year.

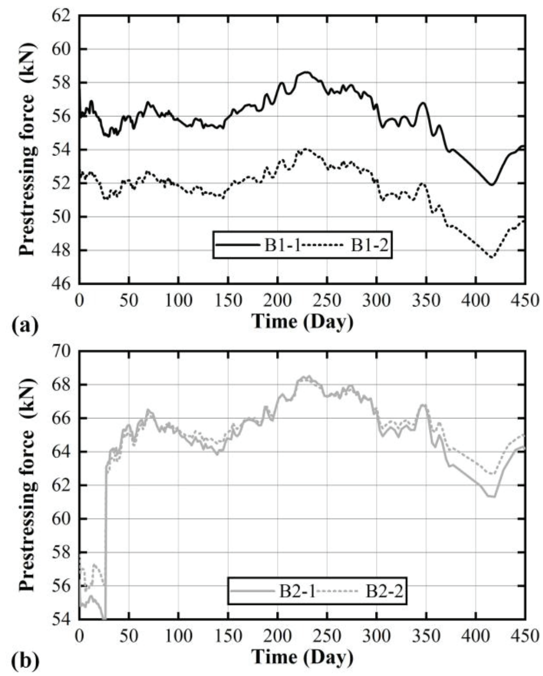

Figure 8. Prestressing force: (a) unloaded group B1; (b) loaded group B2.

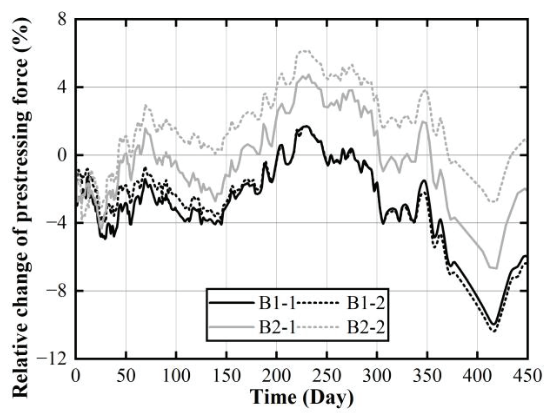

Figure 9. Relative change of prestressing force: the ratio of changes to initial value in which the change caused by applying load is also included.

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Comparing Group B1 and B2, the load pattern had minimal impact on the short-term fluctuations of prestressing force compared to moisture content. The relative changes were approximately -10.2% - 1.7% and -6.7% - 6.1% for Group B1 and B2, respectively. This indicates that loading resulted in less loss and relative loss of prestressing force. This difference can be attributed to the fact that loading is beneficial for the elongation of the prestressing tendon.

4.4 DEFLECTION

The experimental results of the deflection and its relative change are illustrated in **Fig. 9** and **Fig. 10**. The relative change of loaded group B2 before loading is not considered.

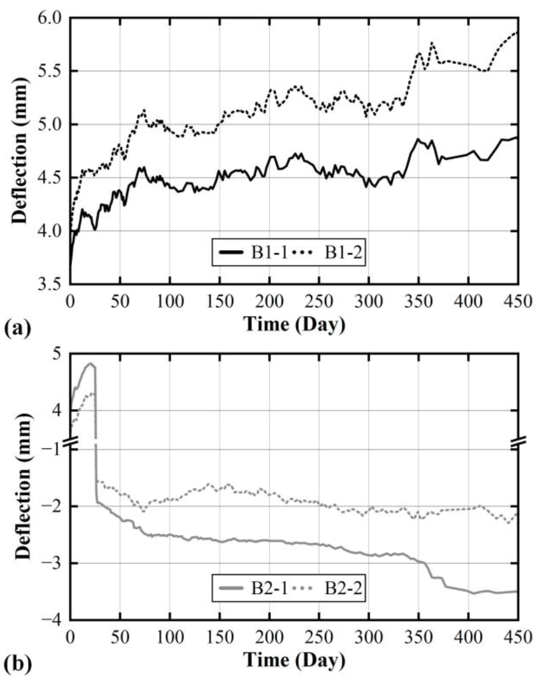

Figure 10. Deflection: (a) unloaded group B1; (b) loaded group B2.

It can be observed that the loading pattern significantly influences the deflection change. Over the long term, Group B1 exhibits a pronounced increasing trend in deflection, while Group B2 shows a decreasing trend. The maximum relative change was 52.8% for Group B1 and 27.3% for Group B2, respectively. This indicates that the relative deflection change of unloaded pattern is much bigger than the loaded pattern in this study. In the short term, the influence of moisture change on Group B1 was more significant than that on Group B2. These aforementioned differences arise from the opposing effects of prestressing force and applied load on deflection. Specifically, the prestressing force causes upward arching of the beam, while the applied load induces downward bending. Their interaction limits the deflection change.

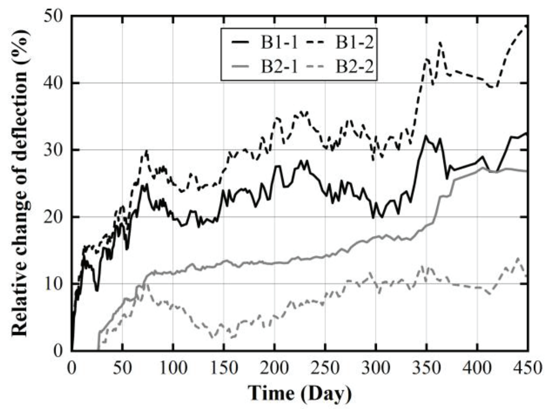

Figure 11. Relative change of deflection.

5 – CONCLUSION

This study conducted a long-term monitoring on unloaded and loaded prestressed glulam beams. The change of moisture content, prestressing force, deflection and strain were recorded for 450 days. The analysis emphasizes the influence of the load pattern.

(1) The moisture content showed a similar changing trend to the relative humidity. Samples with comparable initial moisture content exhibited similar changing trends and amplitudes.

(2) In loaded beams, the prestressing force helps maintain the tensile strain of bottom fiber at a lower level. The environmental factors and the direction of strain significantly influence long-term strain behavior.

(3) The prestressing force showed a similar short-term changing trend to relative humidity and seasonal thermal change due to temperature change. During the testing period, the maximum prestress losses were 10.2% for unloaded beams and 6.7% for loaded beams. The elongation of the prestressing tendon due to loading mitigated the rate of prestress loss.

(4) Deflection is significantly influenced by the loading pattern throughout the entire changing trend. Unloaded beams experienced relative deflection up to 52.8%, while loaded beams experienced creep deflections up to 27.3%. The opposing effect of the prestressing force compared to the applied load can reduce downward creep deflection.

In conclusion, the experimental results indicate that environmental changes and loading patterns should be carefully considered in the engineering practice of prestressed timber beams. Additionally, these long-term experimental monitoring are going to be extended to accurately capture the year-to-year changing trends.

6 – ACKNOWLEDGEMENT

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